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A Joint Program for Agriculture and Resources Inventory Surveys Through Aerospace Remote Sensing

Soil Moisture

January 1982

ANNUAL REPORT: ACCOMPLISHMENTS OF THE NASA JOHNSON SPACE CENTER PORTION OF THE SOIL MOISTURE PROJECT IN FISCAL YEAR 1981

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15. Supplementary Notes

The Agriculture and Resources Inventory Surveys Through Aerospace Remote Sensing is a joint program of the U.S. Department of Agriculture, the National Aeronautics and Space Administration, the National Oceanic and Atmospheric Administration (U.S. Department of Commerce), the Agency for International Development (U.S. Department of State), and the U.S. Department of the Interior.

16. Abstract

The significant accomplishments of the National Aeronautics and Space Administration/Johnson Space Center (NASA/JSC) portion of the AgRISTARS Soil Moisture project are reported.

The NASA/JSC Ground Scatterometer System was used in a row structure and row direction effects experiment to understand these effects on radar remote sensing of soil moisture. Also, a modification of the scatterometer system was begun and is continuing, to allow cross-polarization experiments to be conducted in fiscal years 1982 and 1983. Preprocessing of the 1978 Agricultural Soil Moisture Experiment (ASME) data was completed. Preparations for analysis of the ASME data in fiscal year 1982 were completed. A radar image simulation procedure developed by the University of Kansas is being improved. Profile soil moisture model outputs were compared quantitatively for the same soil and climate conditions. A new model was developed and tested to predict the soil moisture characteristic (water tension versus volumetric soil moisture content) from particle-size distribution and bulk density data. A study of the relationships between surface-zone soil moisture, surface flux, and subsurface moisture conditions was undertaken and is continuing. Investigations were continued into the ways in which measured soil moisture (as obtained from remote sensing) can be used for agricultural applications.

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ANNUAL REPORT: ACCOMPLISHMENTS OF THE NASA JOHNSON SPACE CENTER PORTION OF THE SOIL MOISTURE PROJECT IN FISCAL YEAR 1981

Job Order 71-324

This report describes the activities of the Soil Moisture project of the AgRISTARS program for fiscal year 1981.

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LOCKHEED ENGINEERING AND MANAGEMENT SERVICES COMPANY, INC.

Under Contract NAS 9-15800

For

Earth Resources Research Division

Space and Life Sciences Directorate

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LYNDON B. JOHNSON SPACE CENTER
HOUSTON, TEXAS

January 1982

LEMSCO-17305

PREFACE

The Agriculture and Resources Inventory Surveys Through Aerospace Remote Sensing is a multiyear program of research, development, evaluation, and application of aerospace remote sensing for agricultural resources, which began in fiscal year 1980. This program is a cooperative effort of the U.S. Department of Agriculture, the National Aeronautics and Space Administration, the National Oceanic and Atmospheric Administration (U.S. Department of Commerce), the Agency for International Development (U.S. Department of State), and the U.S. Department of the Interior.

The work which is the subject of this document was performed by the Earth Resources Research Division, Space and Life Sciences Directorate, Lyndon B. Johnson Space Center, National Aeronautics and Space Administration and Lockheed Engineering and Management Services Company, Inc. The tasks performed by Lockheed Engineering and Management Services Company, Inc., were accomplished under Contract NAS 9-15800.

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ABBREVIATIONS

AIRP	Aircraft Instrumentation Research Program
AgRISTARS	Agriculture and Resources Inventory Surveys Through Aerospace Remote Sensing
ASME	Agricultural Soil Moisture Experiment
BARC	Beltsville Agricultural Research Center
CCRS	Canadian Centre for Remote Sensing
CCT	computer-compatible tape
CSMP III	Continuous System Modeling Program
CPU	central processing unit
DED	Development and Evaluation Department, Lockheed-EMSCO
DVM	digital voltmeter
ERRD	Earth Resources Research Division
ESD	Experiment Systems Division
ET	Evapotranspiration
FIREX	Free-Flying Imaging Radar Experiment
FY	fiscal year
GSFC	Goddard Space Flight Center
GSS	Ground Scatterometer System
HH	horizontal transmit, horizontal receive
HV	horizontal transmit, vertical receive
IGARSS '81	1981 International Geoscience and Remote Sensing Symposium
JSC	Lyndon B. Johnson Space Center, Houston, Texas
KSU	Kansas State University
KU CRES	University of Kansas Center for Research
LAI	leaf area index

LARS	Laboratory for Applications of Remote Sensing
Lockheed-EMSCO	Lockheed Engineering and Management Services Company, Inc.
NASA	National Aeronautics and Space Administration
PIP	Project Implementation Plan
pixel	picture element
PP	principal point
rf	radiofrequency
RRI	Renewable Resources Inventory project of the AgRISTARS program
SAR	synthetic aperture radar
SM	Soil Moisture project of the AgRISTARS program
URSI	International Union of Radio Service
USDA	U.S. Department of Agriculture
VH	vertical transmit, horizontal receive
VV	vertical transmit, vertical receive

1. BACKGROUND

According to the Agriculture and Resources Inventory Surveys Through Aerospace Remote Sensing (AgRISTARS) Soil Moisture (SM) Project Implementation Plan (PIP), as revised in fiscal year (FY) 1981, the goal of the project was to develop, test, and evaluate an integrated remote sensor and *in situ* data-gathering capability to obtain soil moisture data over large areas for agricultural and hydrological programs of the U.S. Department of Agriculture (USDA). The total National Aeronautics and Space Administration (NASA) portion of the SM project budget for FY 1981 was $1.4 million; of that, the NASA Johnson Space Center (JSC) was allotted $445,000.

The purpose of this document is to describe the activities funded by the NASA/JSC portion of the overall SM project during FY 1981.

The overall SM project was divided into four elements, as follows:

1. *In situ* Sensor Development and Evaluation
2. Remote Sensor Field Measurements
3. Remote Sensor Aircraft Measurements
4. Modeling and Analysis Work

NASA/JSC was responsible for five subtasks under elements 2, 3, and 4. Element 1 was solely a responsibility of the USDA. Specifically, NASA/JSC was charged in the amended SM PIP with the following subtasks:

- <u>Element 2, task 1 (Thermal and Microwave Field Measurements of Soil Moisture Content)</u>

  Subtask: Conduct controlled experiments for the purpose of acquiring data that will allow statistical determination of the dependence of the radar measurements on agricultural practices (e.g., row height, spacing, and direction and roughness effects versus radar polarization, frequency, and lock angle). Upgrade the NASA/JSC Ground Scatterometer System (GSS) to allow cross-polarization measurements ($82,000).

- <u>Element 3, task 1 (Remote Sensor Aircraft Measurements)</u>

  Subtask: Complete the preprocessing and preliminary analysis of the data taken near Colby, Kansas, as part of the Agricultural Soil Moisture Experiment (ASME) in July and August 1978 ($55,000).

- <u>Element 4, task 1 (Information Extraction Analysis)</u>

  Subtask: Integrate the technical results of university efforts to develop candidate multisensor soil moisture extraction algorithms and to assess the accuracy of these estimates. Investigate the effects of spatial resolution on remote sensing of soil moisture by radar ($108,000).

- <u>Element 4, task 3 (Profile Soil Moisture Modeling)</u>

  Subtask: Develop procedures to estimate soil moisture in the root zone. Use models that will employ readily available weather and soils data and remotely sensed surface soil moisture data. Test models against existing data ($90,000).

- <u>Element 4, task 7 (Agricultural Application of Measured Soil Moisture)</u>

  Subtask: Assess the usefulness of soil moisture information in crop growth, crop development, and yield estimation. Conduct sensitivity studies on the importance of soil moisture in yield ($110,000).

2. SUMMARY OF ACCOMPLISHMENTS

In FY 1981, significant progress was made in each subtask area. The purpose of this section is to summarize the results of the research conducted in FY 1981. Details are given in the sections that follow.

The effects of row direction and large-scale row structure on the radar backscattering of bare, row-plowed fields were investigated in 1980-81. Two experiments had been conducted with the GSS in FY 1980 at two test sites (Jornada test site, Las Cruces, New Mexico, and Prairie View test site, Prairie View A&M University, Prairie View, Texas). One more experiment was conducted at the Jornada test site in FY 1981. All experiments were conducted on bare fields that had been plowed in rows having spacings from 35 to 98 cm. The data from these experiments support the following findings:

1. Row direction effects for bare fields are severe for all frequencies used (1.6, 4.75, and 13.3 GHz) when like polarization (HH)* is used and when the incidence angle is near the approximate slope angle of the sides of the row-plowed furrows.
2. If the azimuthal angles of the radar system are farther away than about 30° from directly across the rows, the effects of row direction are insignificant.
3. The magnitude of the effect is approximately the same as the magnitude of the effect of soil moisture itself (varying from dry to near field capacity conditions) or larger; thus, row direction effects must be considered and accounted for in any soil moisture remote sensing procedure.
4. Row direction effects are insignificant when cross polarization (HV)* is used. Unfortunately, little is known of the information content of cross-polarized radar measurements so far as soil moisture conditions are concerned.

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*Polarization combinations are defined as:
HH = horizontal transmit, horizontal receive
HV = horizontal transmit, vertical receive
VH = vertical transmit, horizontal receive
VV = vertical transmit, vertical receive

In FY 1981, the GSS was modified to enable it to be used in cross-polarization experiments in future years.

Preprocessing of the 1978 ASME data was completed, and software packages were developed to allow the comparison of remotely sensed and ground-truth (soil moisture) ASME data at the sensor footprint level (about 36 by 76 m). Statistical procedures were developed to allow the testing of soil moisture estimation algorithms driven by remotely sensed data. These preparations were made for an extensive analysis of the ASME data in FY 1982. The key difference between the JSC analysis and the analysis by other ASME investigators is that other investigators are comparing field averages of soil moisture data to field averages of remotely sensed data. The JSC effort is aimed at comparing averages of soil moisture and remotely sensed data over the same strip of land surface instead of over the entire field. The remotely sensed data were taken in a strip in each field and not over the entire field.

A contract was awarded to the University of Kansas Center for Research (KU CRES), Lawrence, Kansas, to improve a radar image simulation procedure to be used in the investigation of the effects of spatial resolution on remote sensing of soil moisture by radar. The previous effort by the contractor was based on a doubtful assumption that all land areas evaporated water at the same rate throughout the simulated period of time. More realistic assumptions will be used in the current contracted effort.

In the absence of accurately measured soil moisture profile data, various models were tested against Van Bavel's soil moisture model, WATBAL1 (unpublished), which predicts soil moisture profiles for a given period of time. Also, equipment has been purchased to support soil moisture profile measurements and water budget model testing activities in FY 1982 and beyond. The equipment includes soil moisture meters, such as tensiometers, neutron probes, and drying ovens; weather instruments, such as those which measure wind, temperature, humidity, rainfall, evaporation, and solar radiation; and a soil water characteristic measurement apparatus. During FY 1981, a model to predict the soil moisture characteristic (water tension versus volumetric soil

moisture content) from particle-size distribution and bulk density was developed, refined, and tested against 181 measured data sets.

A major small-plot experiment was conducted at Kansas State University (KSU) to study the relationship between surface-zone soil moisture and winter wheat and sorghum yields. Also, a study was initiated in late FY 1981 on the relationship between surface-zone soil moisture and crop yields for corn and soybeans. A study of the relationships between surface-zone soil moisture, surface flux, and subsurface moisture conditions was undertaken and is continuing.

3. BUDGET AND PERSONNEL

In FY 1981, SM project funds at NASA/JSC were allotted as follows:

Element-task	Contractor or organization	Amount
02-01	Experiment Systems Division (ESD), NASA/JSC, Houston, Tex.	$ 82,000
03-01	Aircraft Instrumentation Research Program (AIRP), NASA/JSC, Houston, Tex.	5,000
	Lockheed Engineering and Management Services Company, Inc. (Lockheed-EMSCO), Houston, Tex.	50,000
04-01	Lockheed-EMSCO	58,000
	University of Kansas Center for Research (KU CRES), Lawrence, Kans.	50,000
04-03	Lockheed-EMSCO	90,000
04-07	Evapotranspiration Laboratory, KSU, Manhattan, Kans.	75,000
	Laboratory for Applications of Remote Sensing (LARS), Purdue University, West Lafayette, Ind.	35,000
Total		$445,000

The primary personnel involved in the NASA/JSC portion of the SM project in FY 1981 were as follows:

Name	Title	Organization
Dr. Jack Paris	Task coordinator and project scientist	NASA/JSC, Earth Resources Research Division (ERRD)
Mr. Richard Fenner	Microwave engineer	NASA/JSC, ESD
Mr. Gerald Pels	Microwave engineer	NASA/JSC, ESD
Dr. Lalit Arya	Soil physicist	Lockheed-EMSCO, Development and Evaluation Department (DED)

Name	Title	Organization
Dr. William Hildreth	Meteorologist	Lockheed-EMSCO, DED
Mr. John Richter	Meteorologist and programmer	Lockheed-EMSCO, DED
Mr. William Rosenkranz	Microwave engineer	Lockheed-EMSCO, DED
Mr. Steven Davidson	Statistician	Lockheed-EMSCO, DED
Dr. Fawwaz Ulaby	Microwave scientist	KU CRES
Mr. Craig Dobson	Microwave scientist	KU CRES
Dr. Ed Kanemasu	Agronomist	KSU
Mr. Dan Lawlor	Agronomist	KSU
Dr. Marvin Bauer	Agronomist	LARS

4. ORGANIZATIONAL ROLES

The role of ERRD was to coordinate SM project tasks at NASA/JSC and to perform analyses of the data acquired in SM project experiments.

The role of ESD was to conduct the field experiments at the Prairie View test site in September 1980 and at the Jornada test site in November 1980 and to preprocess the data so acquired. Also, ESD carried out the modifications to the GSS.

The role of AIRP was to preprocess the aircraft remote-sensor data acquired during the ASME in 1978.

The role of Lockheed-EMSCO was to complete the preprocessing of ground-truth data for the ASME, to complete the preparation of acetate overlays showing the locations of the centers of aircraft photographs taken during the ASME, and to develop software packages to be used in the further processing and analysis of ASME data (scheduled for FY 1982). Lockheed-EMSCO also developed statistical procedures to test algorithms that use remotely sensed data to estimate soil moisture content. In addition, Lockheed-EMSCO studied various soil moisture profile models to determine their relative performance; developed a new soil water characteristic prediction model; and began an investigation of the possible relationship between rate of surface evaporation or infiltration and frequent surface-zone soil moisture measurements which might be made from remotely sensed data.

The role of KU CRES was to initiate improvement in a synthetic aperture radar (SAR) imager data simulation model developed previously under a NASA grant from NASA/Goddard Space Flight Center (GSFC) at Greenbelt, Maryland. The simulation model had been used to investigate the effects of SAR spatial resolution on the performance of a simple algorithm (C-band HH polarization at 15° incidence angle) used for estimating soil moisture condition from SAR data. The previous model assumed a constant rate of evaporation over the image area (17.6 by 19.2 km, or 11 by 12 miles) and thus led to an artificially smooth distribution

in "true" soil moisture content. A more realistic model for evaporation is now being incorporated into the simulation model.

The role of KSU and LARS was to investigate the usefulness of measured surface-zone soil moisture for agricultural applications such as the estimation of planting date distribution, crop growth stage, and crop grain yield for wheat and sorghum (KSU) and for corn and soybeans (LARS). KSU also conducted a series of small-plot experiments at KSU experimental farms to study the problem. The effort at LARS started late in FY 1981.

5. SPECIFIC ACCOMPLISHMENTS

5.1 SIGNIFICANT MEETINGS AND BRIEFINGS

The SM task coordinator presented a portion of the status and plan for the SM project to the NASA Technical Assessment Working Group at NASA/JSC on December 5, 1980, and subsequently attended the following significant briefings and meetings.

- On December 9, 1980, along with Dr. Howard Hogg of NASA Headquarters, visited Dr. Joe Ritchie at the Blacklands Experiment Station, Temple, Texas.
- On January 5 through 8, 1981, attended a meeting of the International Conference on Signature Problems for Microwave Sensing of Land and Oceans sponsored by the International Union of Radio Science (URSI), at the University of Kansas.
- On March 11 through 13, 1981, briefed two committees of the Great Plains Council on the status of soil moisture research at their meeting at NASA/JSC.
- On March 17, 1981, presented the results of the row-structure and row-direction effects research for radar at the Quarterly Technical Interchange meeting at NASA/JSC.
- On March 18 through 20, 1981, presented the results of the soil moisture research in FY 1980 and 1981 at the meeting of the SM working group at the Beltsville Agricultural Research Center (BARC) in Beltsville, Maryland.
- Served as cochairman of the Free-Flying Imaging Radar Experiment (FIREX) Renewable Resources Inventory (RRI) Study Team that met on several occasions at NASA/JSC, NASA/GSFC, NASA Headquarters in Washington, D.C., and the Canadian Centre for Remote Sensing (CCRS) in Ottawa, Ontario, Canada.
- On July 23, 1981, chaired a briefing on "Spectral Inputs to Yield" for AgRISTARS Level 2 Manager W. E. Rice.
- On September 21, 1981, participated in a meeting at BARC, the purpose of which was to write the FY 1981-1982 SM PIP.

In addition, he compiled weekly, biweekly, monthly, and quarterly status reports throughout FY 1981 for line and project management.

NASA/JSC engineers Fenner and Pels presented a paper on row-structure effects on radar at the 1981 International Geoscience and Remote Sensing Symposium (IGARSS '81) in Washington, D.C., on June 8 through 10, 1981. In March 1981, Lockheed-EMSCO scientists attended the meeting of the SM working group at BARC.

5.2 SM PROJECT PUBLICATIONS

In FY 1981, SM project scientists completed the following publications at NASA/JSC.

- Arya, L. M.: Agricultural Soil Moisture Experiment, Colby, Kansas, 1978: Measured and Predicted Hydrologic Properties of the Soil. SM-L0-00463, JSC-16366, LEMSCO-14307, NASA/JSC (Houston), Oct. 1980.
- Arya, L. M.; and Phinney, D. E.: Evaluation of Gravimetric Ground-Truth Soil Moisture Data Collected for the Agricultural Soil Moisture Experiment, 1978, Colby, Kansas, Aircraft Mission. SM-L0-00441, JSC-16357, LEMSCO-14600, NASA/JSC (Houston), Oct. 1980.
- Arya, L. M.; and Hildreth, W. W.: Agricultural Soil Moisture Experiment: Evaluation of the 1978 Colby Data Collected for Comparative Testing of Soil Moisture Models. SM-L1-04047, JSC-17115, LEMSCO-15324, NASA/JSC (Houston), May 1981.
- Arya, L. M.; and Paris, J. F.: A Physioempirical Model to Predict the Soil Moisture Characteristic From Particle-Size Distribution and Bulk Density Data. Soil Sci. Soc. America J. (To be published, 1981).
- Fenner, R. G.; Pels, G. L.; and Reed, S. C.: A Parameter Study of Tillage Effects on Radar Backscatter. Paper presented at International Geoscience and Remote Sensing Symposium (Washington, D.C.), June 8-10, 1981, vol. II, pp. 1294-1308.
- Hildreth, W. W.: Comparison of the Characteristics of Soil Water Profile Models. SM-L0-00490, JSC-16818, LEMSCO-15330, NASA/JSC (Houston), Jan. 1981.

- Hildreth, W. W.: Description and Sensitivity Analyses of WATBAL1: A Dynamic Soil Water Model. SM-LO-04021, NASA/JSC-16846, LEMSCO-15672, NASA/JSC (Houston), Mar. 1981.
- Kanemasu, E. T.; and Lawlor, D.: Use of Soil Moisture Information in Crop Yield Models. AgRISTARS SM-MO-00496, Kansas State University (Manhattan, Kansas), 1980, pp. 1-54.
- Paris, J. F.; and Arya, L. M.: Experiment Plan: Row and Roughness Effects on Dependence of Active Microwave Measurements of Soil Moisture. SM-JO-00613,, JSC-16822, LEMSCO-15181, Oct. 1980.
- Richter, J. C.: Ground Registration of Data From an Airborne Multifrequency Microwave Radiometer (MFMR). SM-L1-04118, JSC-17152, LEMSCO-16800, NASA/JSC (Houston), Sept. 1981.
- Richter, J. C.: Ground Registration of Data From an Airborne Scatterometer. SM-L1-04091, JSC-17296, LEMSCO-16340, NASA/JSC (Houston), June 1981.

In addition, the following documents are currently in draft form and are scheduled for publication in the near future:

- Preliminary Results of a Study of the Relationship Between Surface Water Flux and Surface Soil Moisture Content, by L. M. Arya.
- A Comparison of Soil Moisture Characteristics Predicted by the Arya-Paris Model With Laboratory-Measured Data, by L. M. Arya, J. C. Richter, S. A. Davidson, and J. F. Paris.
- Plan for the Analysis of the Colby ASME Remote Sensing for Near-Surface Soil Moisture Prediction, by S. A. Davidson.
- Sensitivity Analysis of Saxton's Soil Moisture Profile Model, by W. W. Hildreth.
- A Technique for Assignment of Ground Truth to Microwave Sensor Measurements, by J. C. Richter.

5.3 ROW-STRUCTURE AND ROW-DIRECTION EFFECTS ON RADAR SENSING OF SOIL MOISTURE

In past investigations, researchers have found that the best linear correlation between the radar backscattering coefficient ($\sigma°$) and surface-zone soil moisture (represented as a percentage of volumetric water content at 1/3 bar, θ_{FC}) occurs for a radar configuration as follows: C-band (4.25 GHz) HH at 7° to 17° incidence angle measured from nadir, as shown in figure 1 (Bradley and Ulaby, 1981). While this configuration appears to be the best single sensor configuration for active microwave remote sensing, it has been recognized that, in some cases, significant variations in $\sigma°$ can occur because of row-structure changes and changes in the orientation of the row with respect to the azimuthal look angle of the radar (i.e., when the radar looks across or along rows or in between). For example, a study of the backscattering by sorghum fields (Batlivala and Ulaby, 1975) showed a difference of about 7 dB in the backscattering coefficient when one looks across and along the rows. (See figure 2.) This difference, defined as the look direction modulation function, $\Delta\sigma^\circ_{dB}$ or M_{dB}, is given as follows:

$$\Delta\sigma^\circ_{dB} = M_{dB} = \sigma^\circ_{\perp dB} - \sigma^\circ_{\parallel dB} \tag{1}$$

where $\sigma^\circ_{\perp}$ is measured across rows and $\sigma^\circ_{\parallel}$ is measured along rows. In a later report by Ulaby and Bare (1978), a significant difference in $\sigma°$ was noted for different row directions for corn, wheat, and soybean fields when the microwave frequency was less than about 4 GHz. These findings seemed to suggest that, under vegetated conditions, row-direction changes are not a significant cause of variations in $\sigma°$ when C-band (4.75 Ghz) or higher frequencies are used with like polarization (either HH or VV). When cross-polarization (either HV or VH) is used, the observations support the notion that row-direction changes do not cause significant variations in $\sigma°$, at least for the frequencies and angles used. Figures 3 through 5 show examples of the measurements made by Ulaby and Bare (1978) on corn, soybean, and wheat fields.

Early analyses of the ASME data (Bradley and Ulaby, 1980) show significant effects of row direction for all three radar scatterometers used (L-band at 1.6 GHz, C-band at 4.75 GHz, and Ku-band at 13.3 GHz) when like polarization was used for a wheat stubble field. (See figure 6.) These results do not

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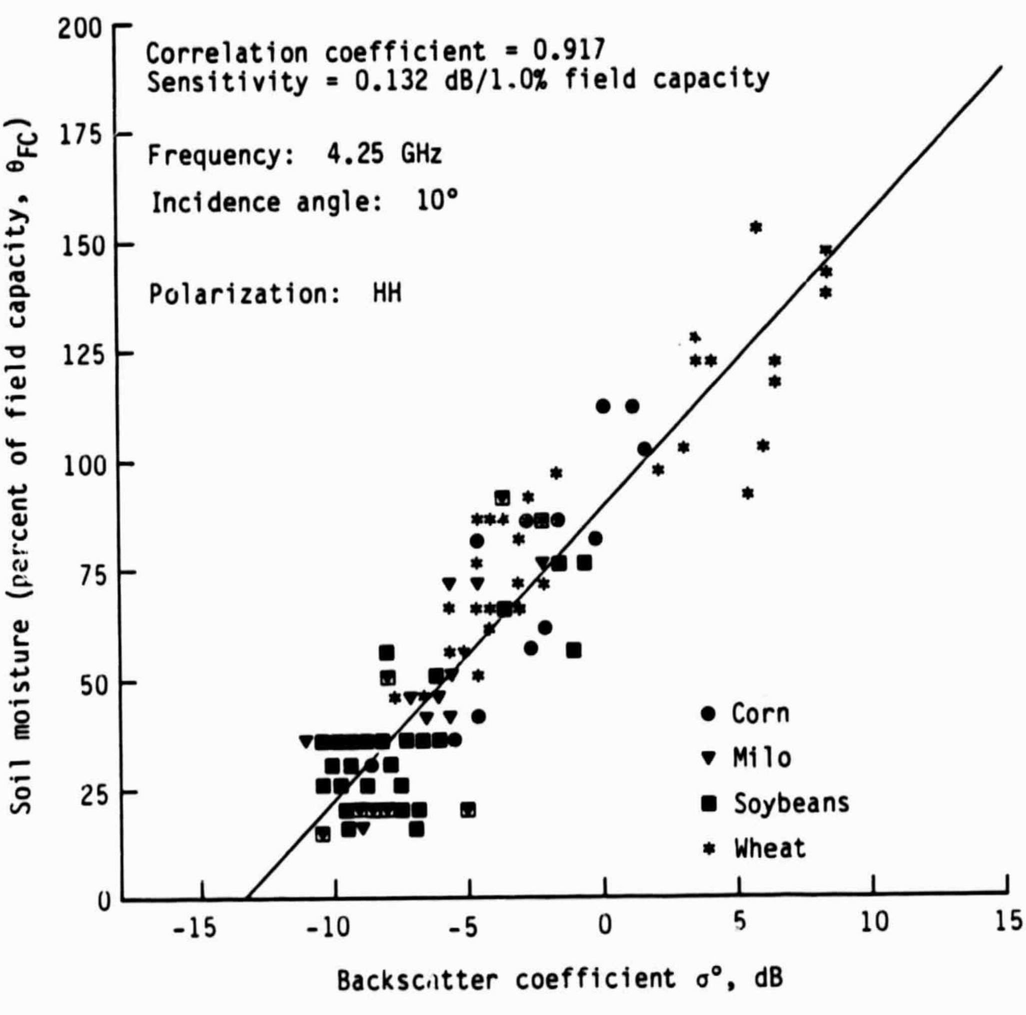

Figure 1.- Soil moisture versus backscattering coefficient at 4.25 GHz, HH, 10° incidence angle (Bradley and Ulaby, 1981).

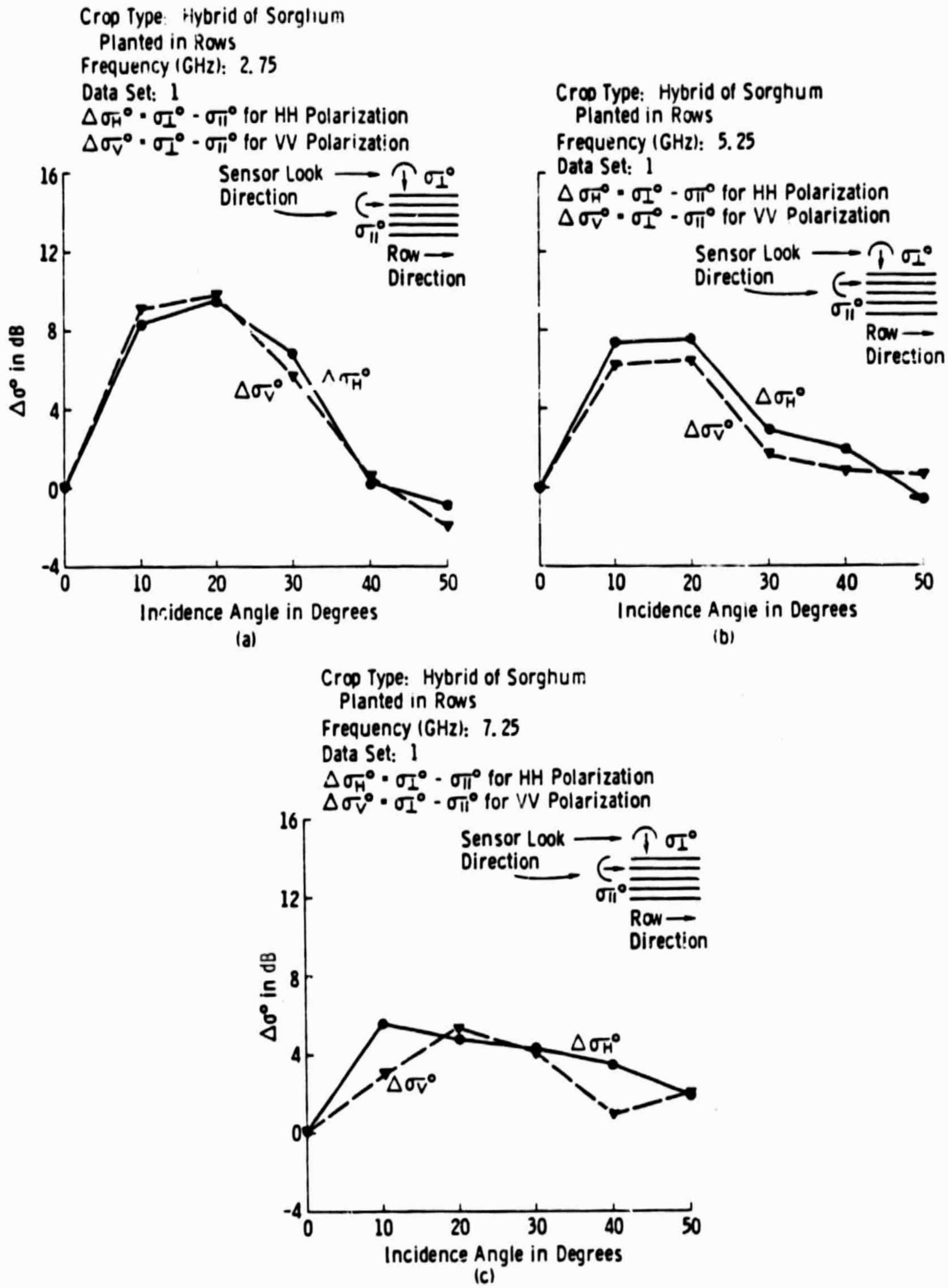

Figure 2.- Graphs of $\Delta\sigma° = \sigma^\circ_\perp - \sigma^\circ_\parallel$, as a function of incidence angle at (a) 2.75 GHz, (b) 5.25 GHz, and (c) 7.25 GHz. Data set 1, July 16, 1974 (Batlivala and Ulaby, 1975).

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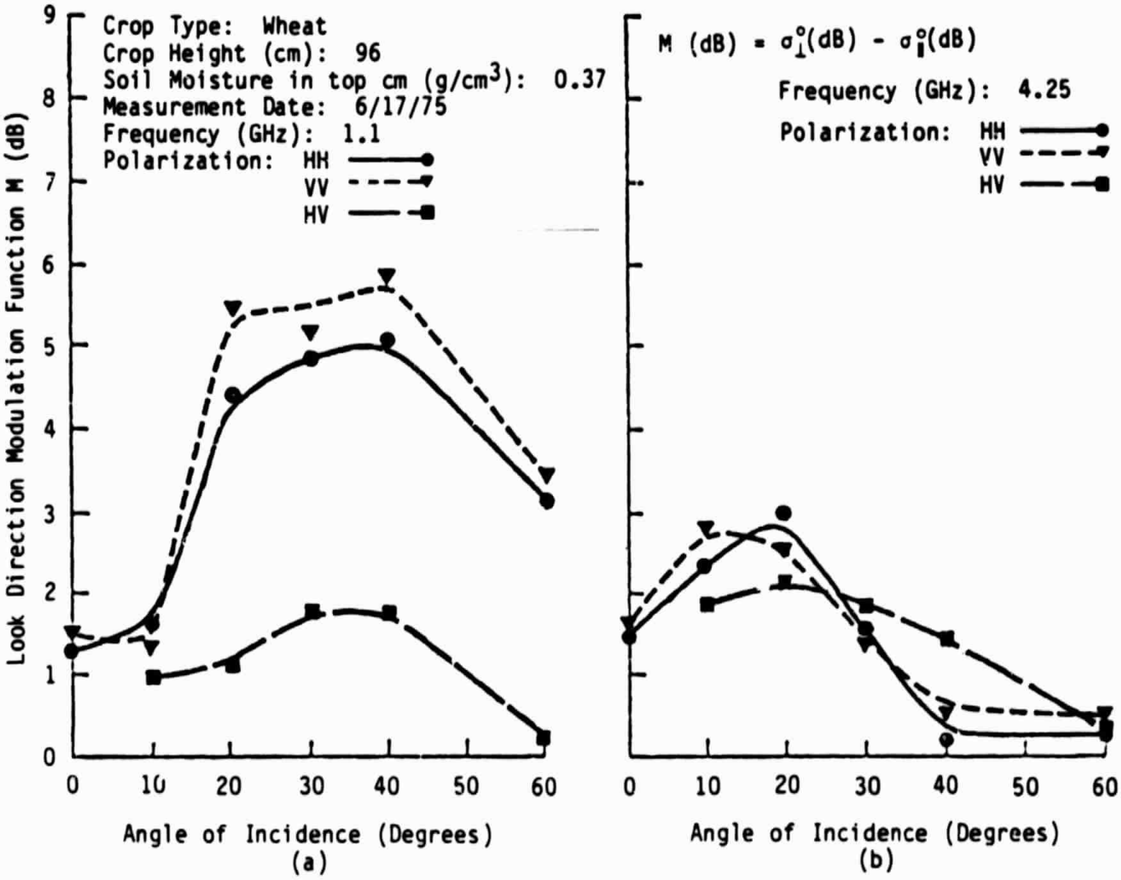

Figure 3.- Comparison of the angular responses of the look direction modulation function of a wheat field for HH, HV, and VV polarizations at (a) 1.1 GHz and (b) 4.25 GHz. (Adapted from Ulaby and Bare, 1978.)

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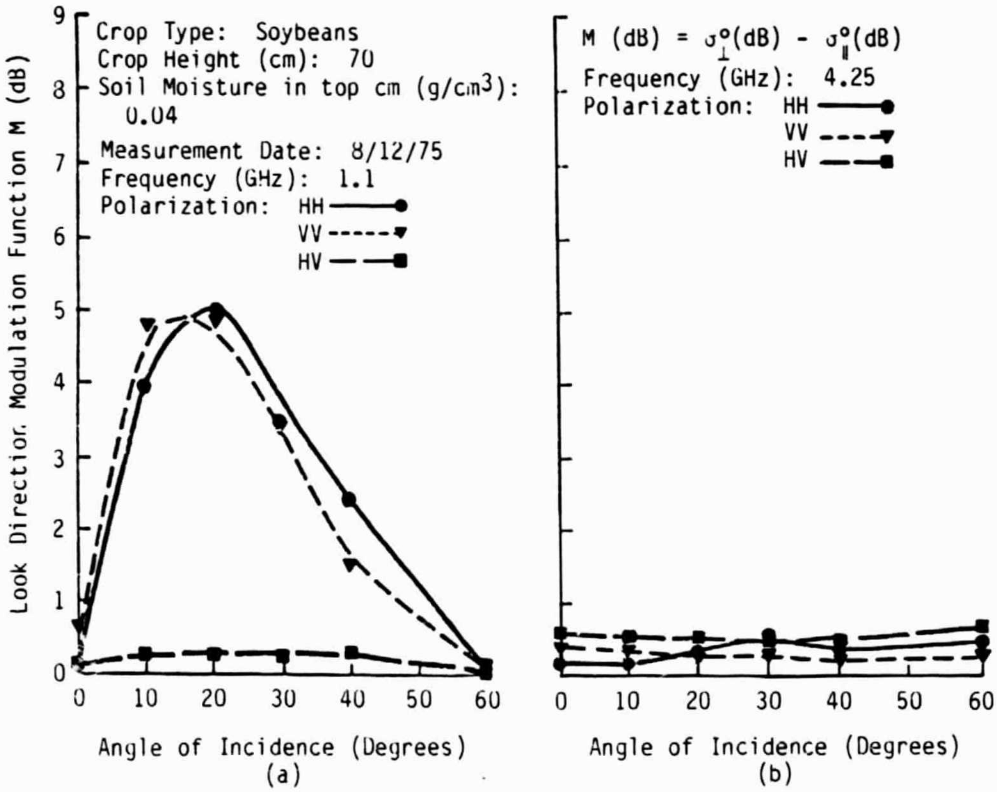


Figure 4.- Comparison of the angular responses of the look direction modulation function of a soybean field for HH, HV, and VV polarizations at (a) 1.1 GHz and (b) 4.25 GHz. (Adapted from Ulaby and Bare, 1978.)

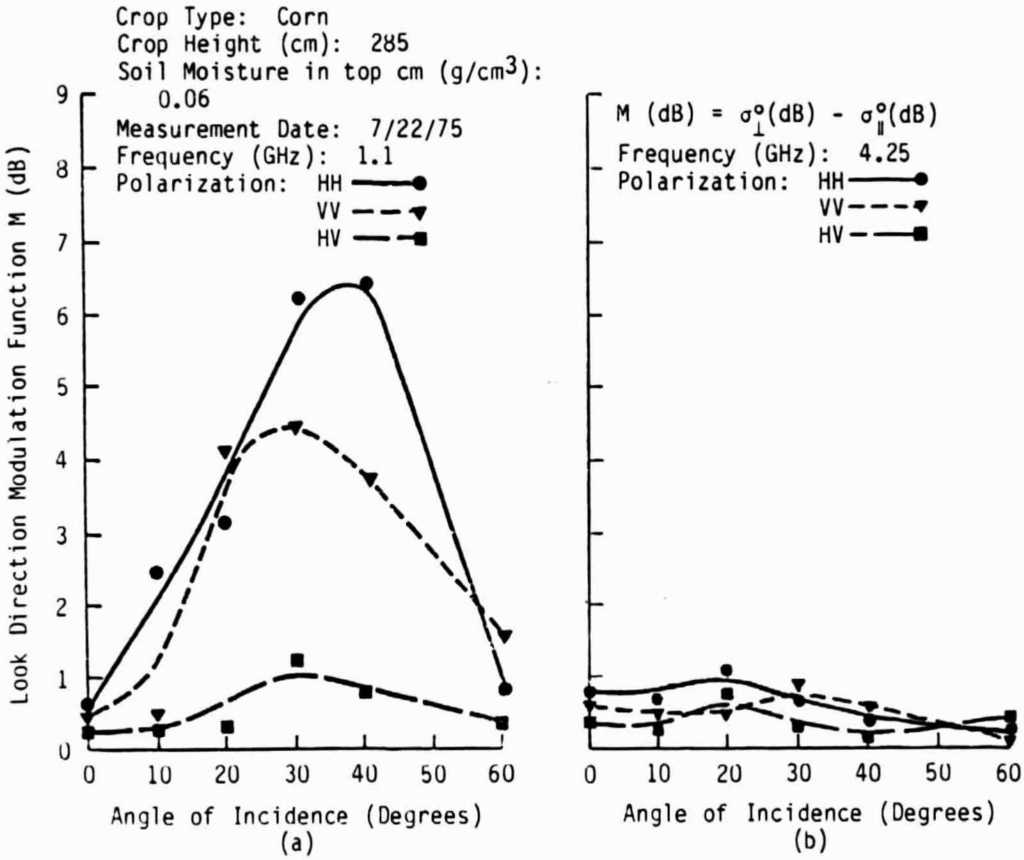
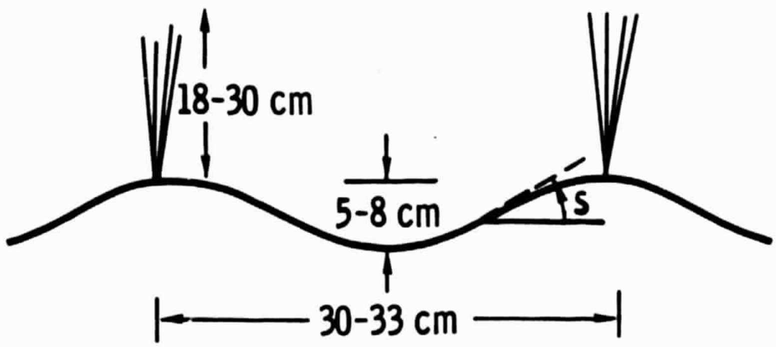
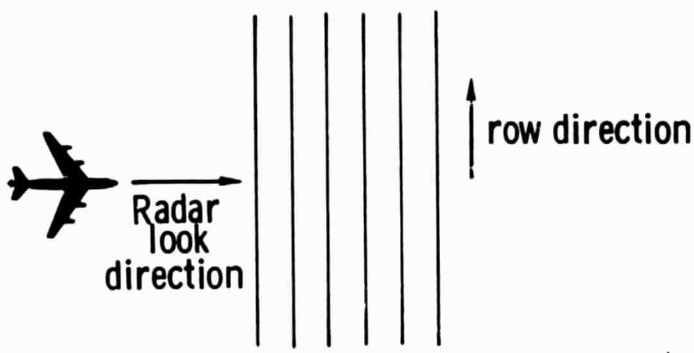


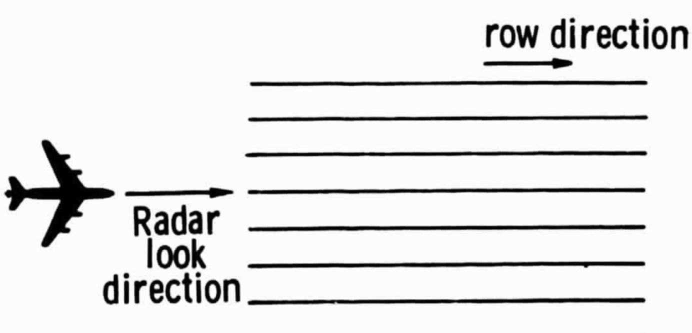
Figure 5.- Comparison of the angular responses of the look direction modulation function of a corn field for HH, HV, and VV polarizations at (a) 1.1 GHz and (b) 4.25 GHz. (Adapted from Ulaby and Bare, 1978.)



(a) Tillage row pattern for the wheat stubble fields measured in the 1978 ASME (Colby, Kansas). The slope s was between 17° and 28°.



(b) Geometry for ⊥ row pattern measurements.



(c) Geometry for ∥ row pattern measurements.

Figure 6.- Tillage row patterns present on 20 of the test fields (ASME 1978, Colby, Kansas). The aircraft radar took measurements in both the ⊥ and ∥ directions (Bradley and Ulaby, 1980).

disagree with those above since the fields in question here are essentially vegetation free. Figure 7 shows the results of aircraft scatterometer measurements on a typical wheat stubble field for like and cross-polarization combinations. In the case of cross-polarization, some of the measurements (circled in fig. 7) are in doubt. This uncertainty is due to the fact that, because of the limiting isolation (20 dB) of the antenna systems used, the measured value of σ° for cross-polarization cannot be less than 20 dB below the corresponding like polarization measurement. Apparently, the row-direction effects on cross-polarized data, seen in figure 7 at 1.6 GHz, are not valid.

In FY 1979, a soil moisture experiment was conducted at NASA/JSC to study the effects of row structure and row direction in the Jornada test site. A report by Fenner et al. (1981) shows the results of this experiment. (See figures 8 through 17.) Note the significant effects (5 to 18 dB) of row direction at incidence angles near 10° to 20°. Again, these results are for like polarization.

Based upon these investigations, more experiments were planned (Paris and Arya, 1980) for a test site on the Prairie View A&M University farm at Prairie View, Texas. The test site in this case was located in a climate more humid than that of previous experiments. Therefore, an experimental design was adopted that would be valid under conditions of changing soil moisture during data acquisition (lasting about 48 hrs). The Ground Scatterometer System (GSS) was moved across the field diagonally. At each point, measurements were made along the row and across the row alternately. Thus, changing soil moisture conditions during the experiment would not affect the measurement of the difference in backscatter (since soil moisture changes affect both measurements in the same way and by the same amount). This design would be recommended for any test site to minimize such factors as temporal changes in soil moisture and small-scale roughness. Figure 18 shows the test site layout. The planned experiment was conducted on two occasions at the Prairie View test site, once on September 15 through 17, 1980, and once on September 22 through 24, 1980. On the first occasion, the field was plowed in deep furrows with a width of 98 ± 10 cm and a depth (top to bottom) of 24 ± 6 cm. On the second occasion, the width was 35 ± 2 cm, and the depth was 10 ± 1.5 cm. (See figure 19 for

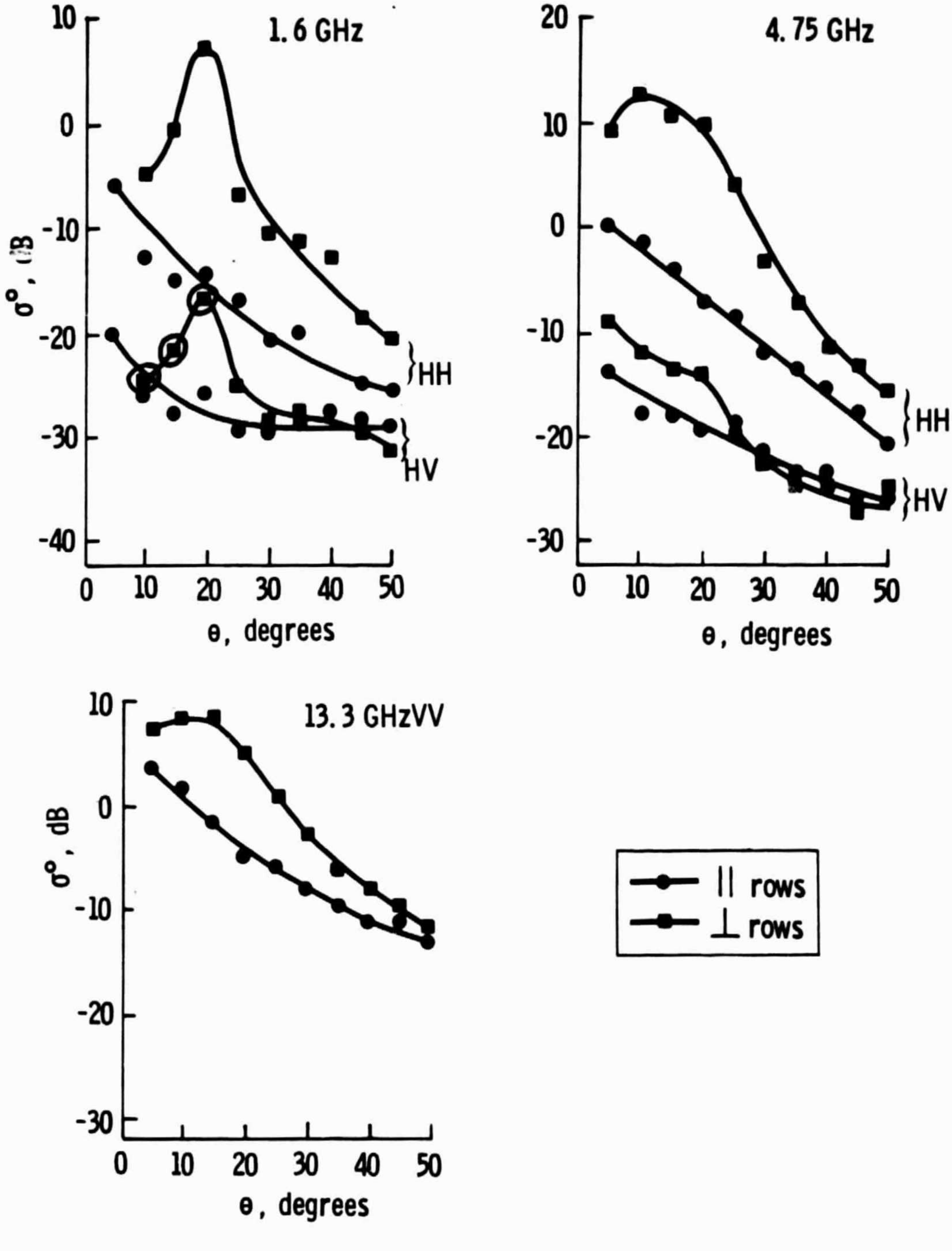


Figure 7.- Effect of field row direction on radar backscatter. The cross-polarization response was less affected than the like polarization response; the field was wheat stubble with the row pattern shown in figure 6(a); and soil moisture θ_{FC}(0 to 5 cm) was 87.9 percent (ASME 1978, Colby, Kansas; from Bradley and Ulaby, 1981.)

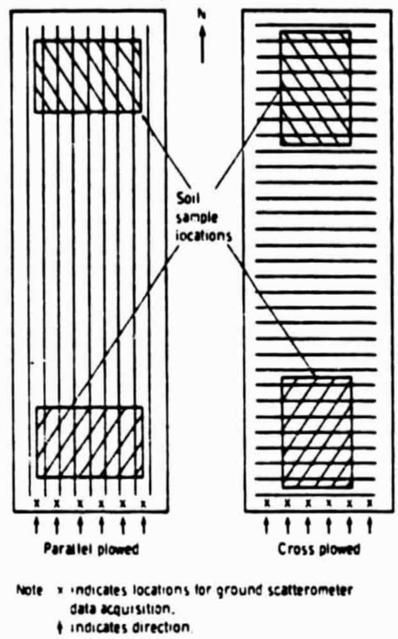


Figure 8.- Ground scatterometer and soil sample locations, Jornada test site (from Fenner et al., 1981).

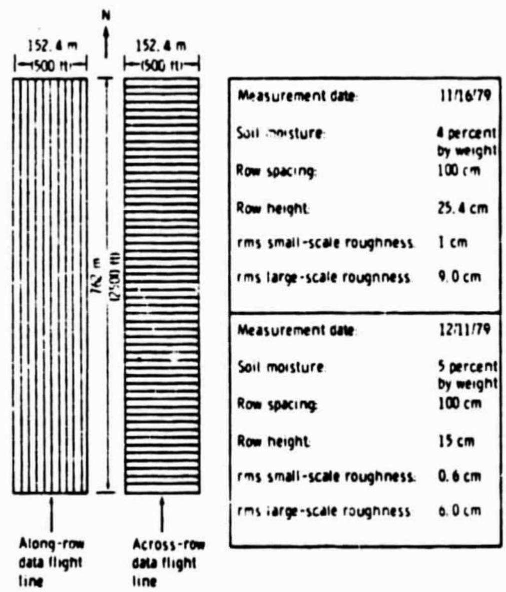


Figure 9.- Test site configuration at times of aircraft data acquisition, Jornada test site (from Fenner et al., 1981).

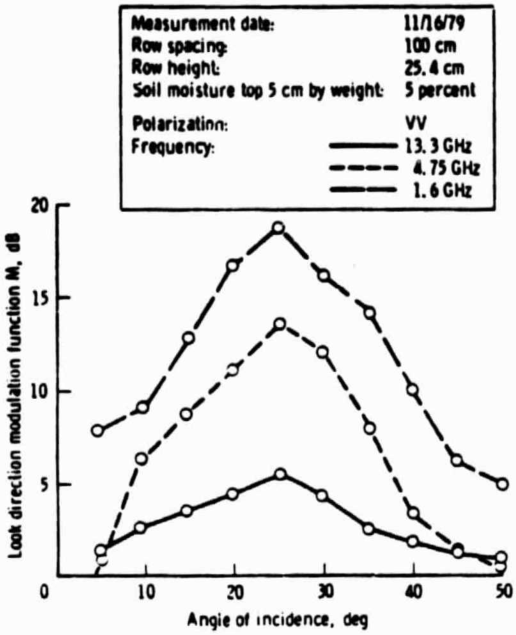


Figure 10.- Comparison of angular responses of the modulation function of a bare field for three frequencies on November 16, 1979 (from Fenner et al., 1981).

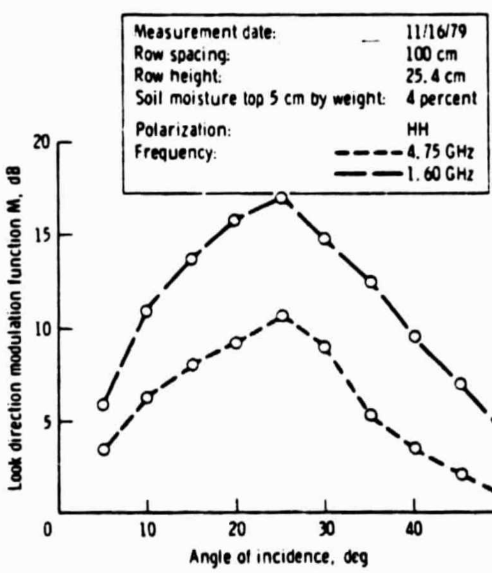


Figure 11.- Comparison of angular responses of the modulation function of a bare field for two frequencies on November 16, 1979 (from Fenner et al., 1981).

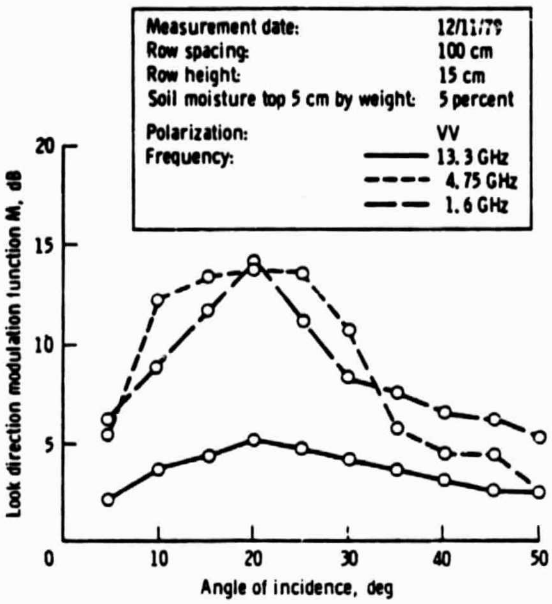


Figure 12.- Comparison of angular responses of the modulation function of a bare field for three frequencies on December 11, 1979 (from Fenner et al., 1981).

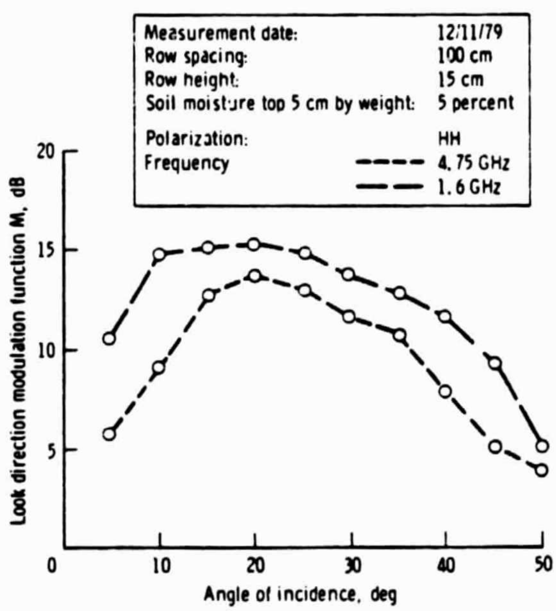


Figure 13.- Comparison of angular responses of the modulation function of a bare field for two frequencies on December 11, 1979 (from Fenner et al., 1981).

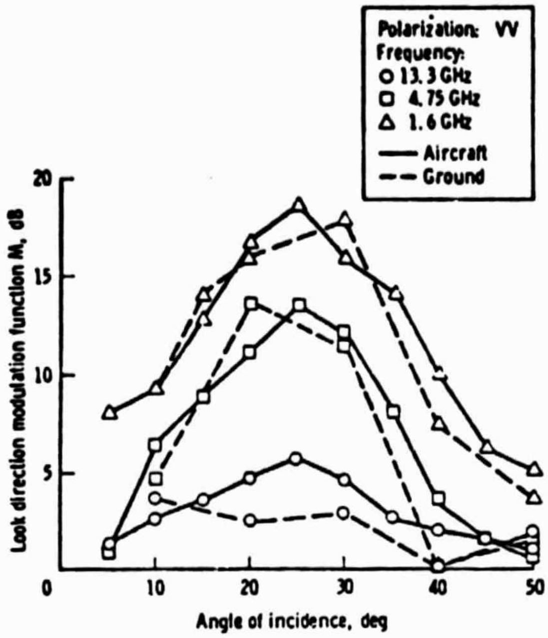


Figure 14.- Comparison of aircraft- and ground-acquired angular responses (from Fenner et al., 1981).

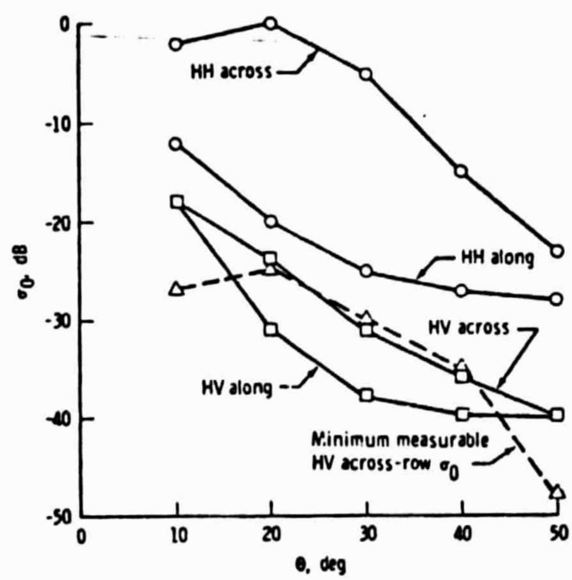


Figure 15.- 1.6-GHz $\sigma°$ compared to incidence angle for across- and along-row viewing directions (from Fenner et al., 1981).

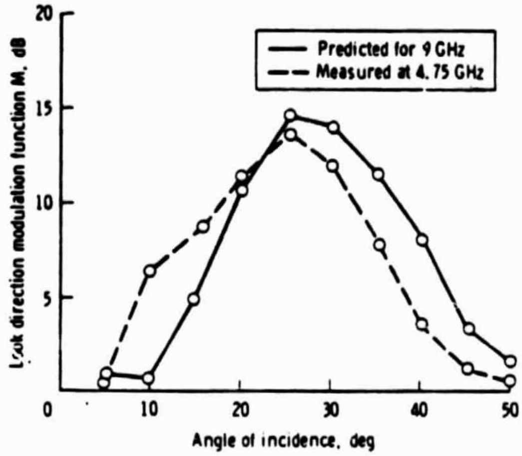


Figure 16.- Comparison of measured and predicted values of the modulation function angular response (from Fenner et al., 1981).

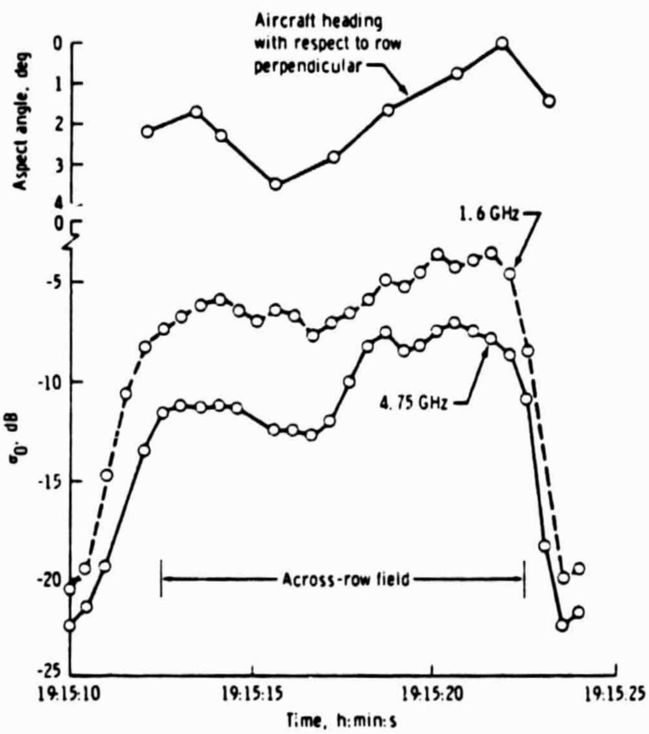


Figure 17.- Time history of 20° incidence angle (4.75 and 1.6 GHz σ°) plotted with aspect angle (from Fenner et al., 1981).

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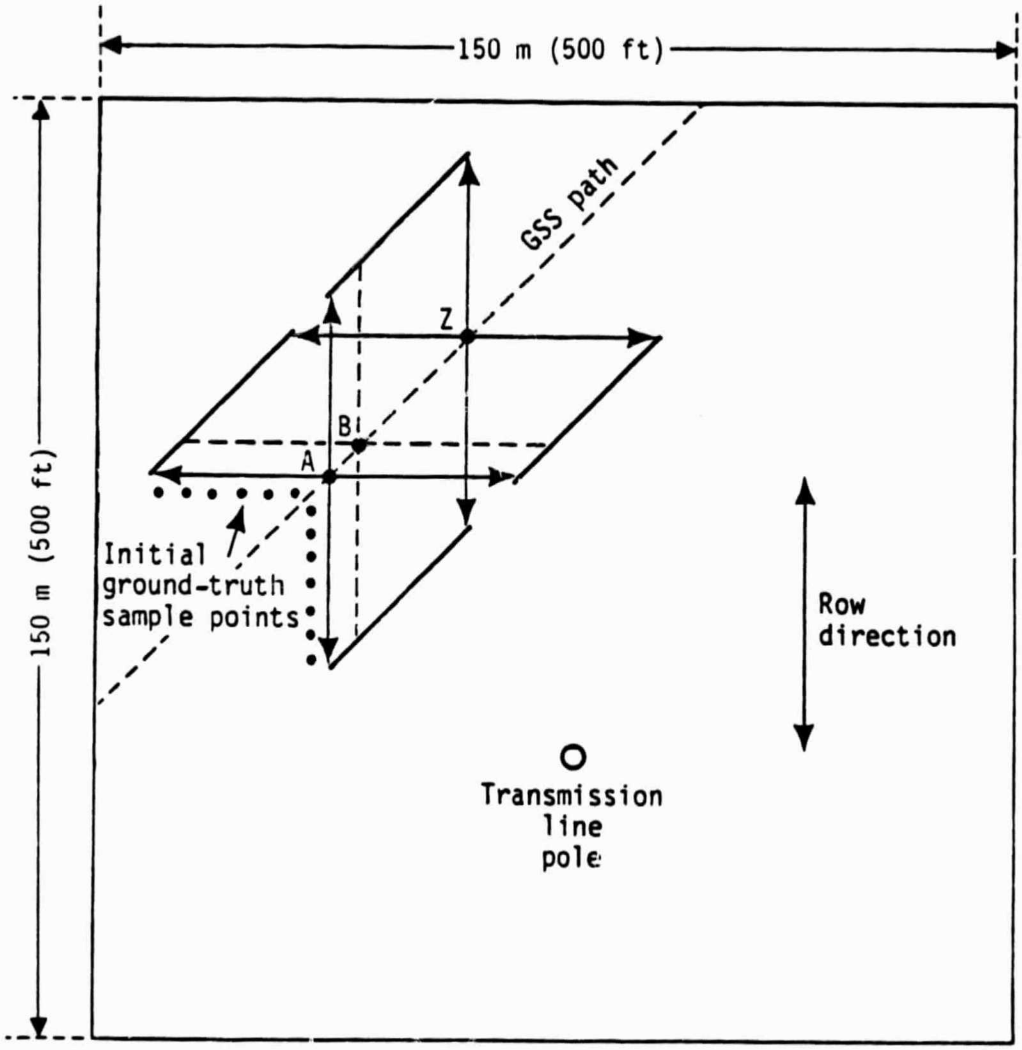

Figure 18.- Prairie View test site.

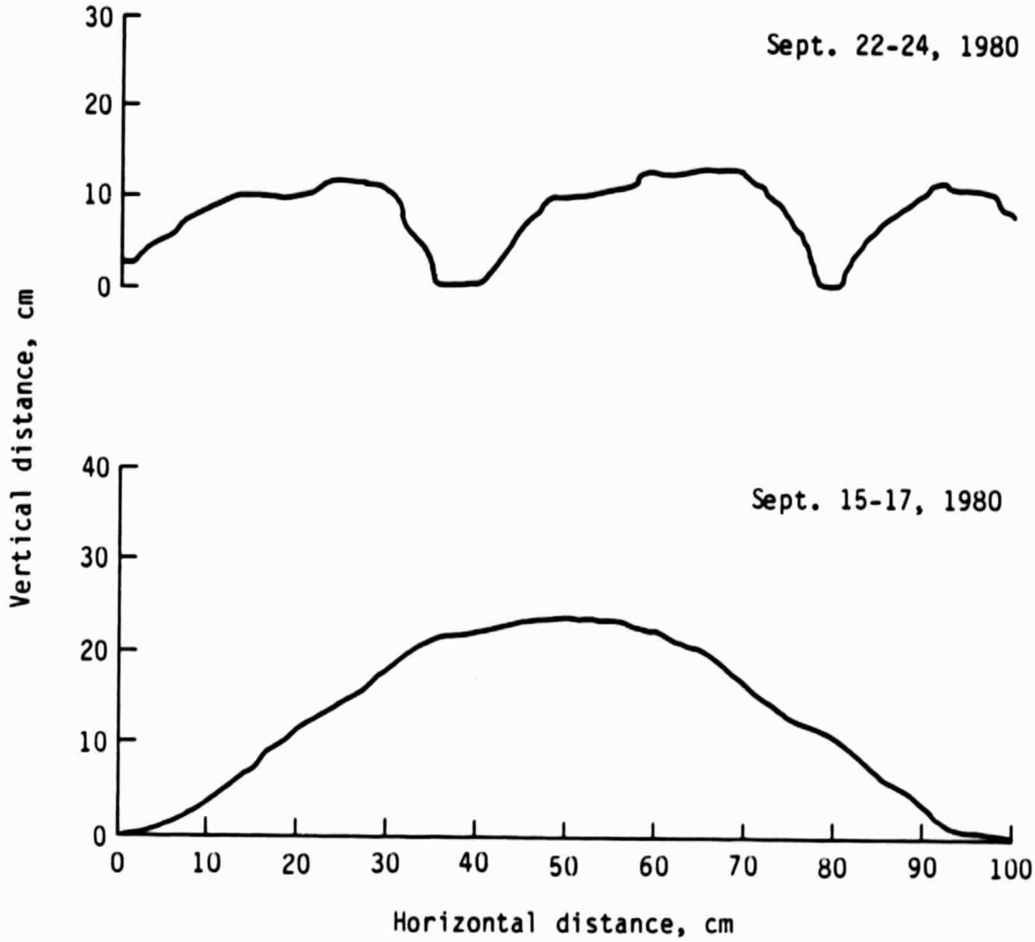

Figure 19.- Typical ridge-furrow cross-sections at the Prairie View experimental site.

typical ridge-furrow cross-sections.) It did not rain during either experiment, and the temporal fluctuations in observed soil moisture (mean of 16 samples per observation) were small. (See figure 20.) The results of the measurements at the Prairie View test site are shown in figures 21 and 22.

Note that the look direction modulation function (M) is significant for all bands, especially for incidence angles of 15° or more. The measurements at 10° may not be valid because of the closeness of the footprint to the base of the tower that supports the GSS in the field. Note also, that like polarization was used.

On November 17 through 21, 1980, the GSS was used in an experiment at the Jornada test site. The purpose of this experiment was to investigate how rapidly the transition occurs from large backscattering at across-the-row viewing angles to the smaller backscattering at along-the-row viewing. Measurements of the backscattering coefficient were made by the GSS for incidence angles from 10° to 30° in 5° steps at azimuth angles from 0° to 15° from across-the-row viewing. The results of these measurements are shown in figures 23 and 24. Data from the Prairie View experiments are shown in figure 24 also to illustrate the generally good calibration of the GSS from one date to another and to supply the 90° data points in figure 23. Extrapolation reveals that the effect of row direction is insignificant if azimuth angles are confined to about 40° to 90° from the across-the-row direction. This implies that one strategy in dealing with row-direction effects is to design satellite SAR acquisitions so that the fields are viewed from azimuth angles in the northeast, southeast, southwest, or northwest cardinal directions. This configuration would reduce the number of fields that might suffer row-direction effects, since most fields in the United States are plowed north-south or east-west. Alternately, one could use more than one azimuthal orientation to the SAR by viewing on two or more passes in the same location at approximately right angles. Another idea is to estimate the row direction as a desired piece of information; row-direction effects can have significant effects on optical region (visible and infrared) scanner data when row crops are present. This is because of the differences in the shadowing of sunlight under different row orientations (Suits, unpublished). Finally, it is anticipated that the apparent row-direction independence of cross-polarized

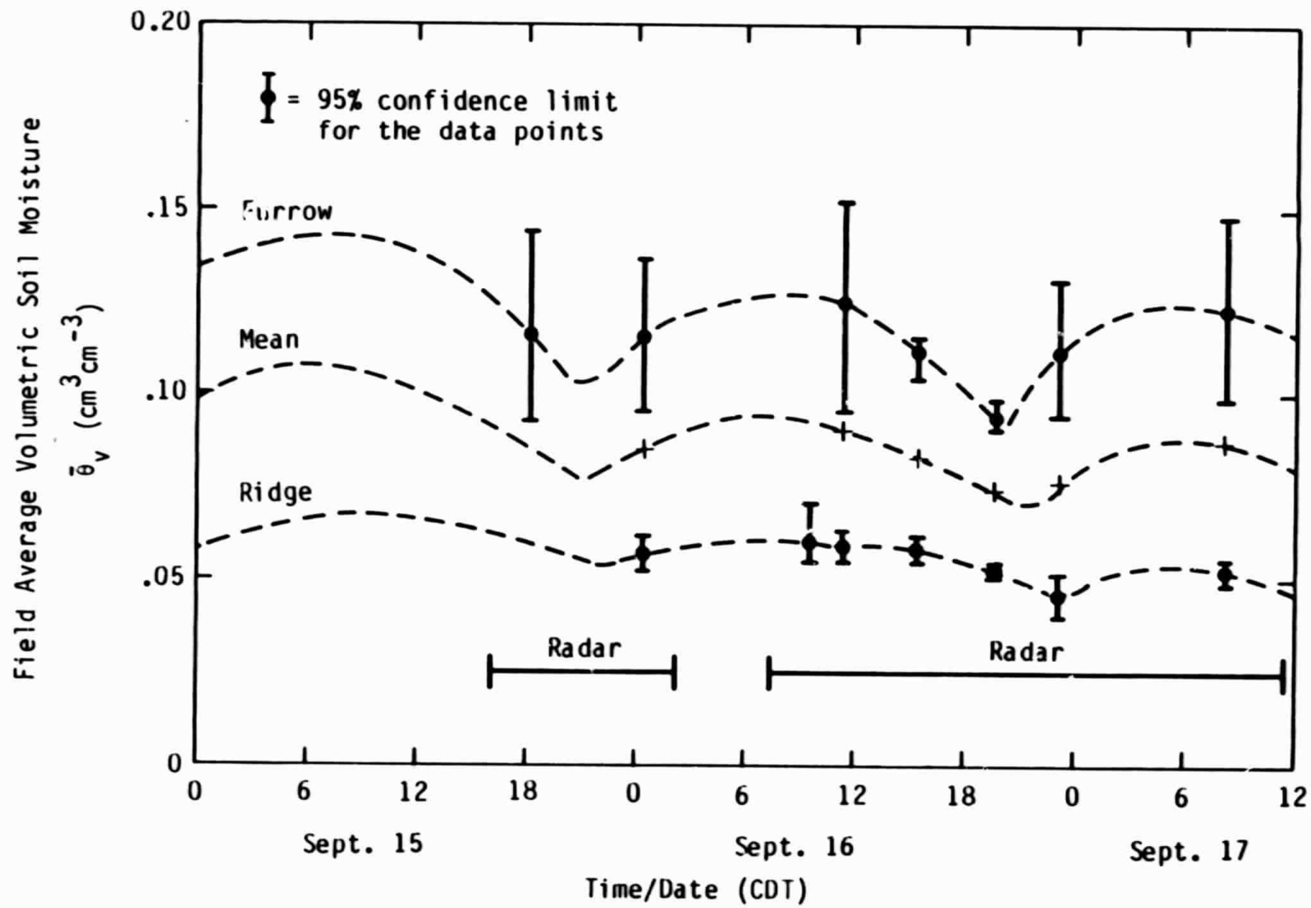

Figure 20.- Temporal fluctuations in surface (0 to 5 cm depth) soil moisture during Prairie View experiments on September 15 through 17, 1980.

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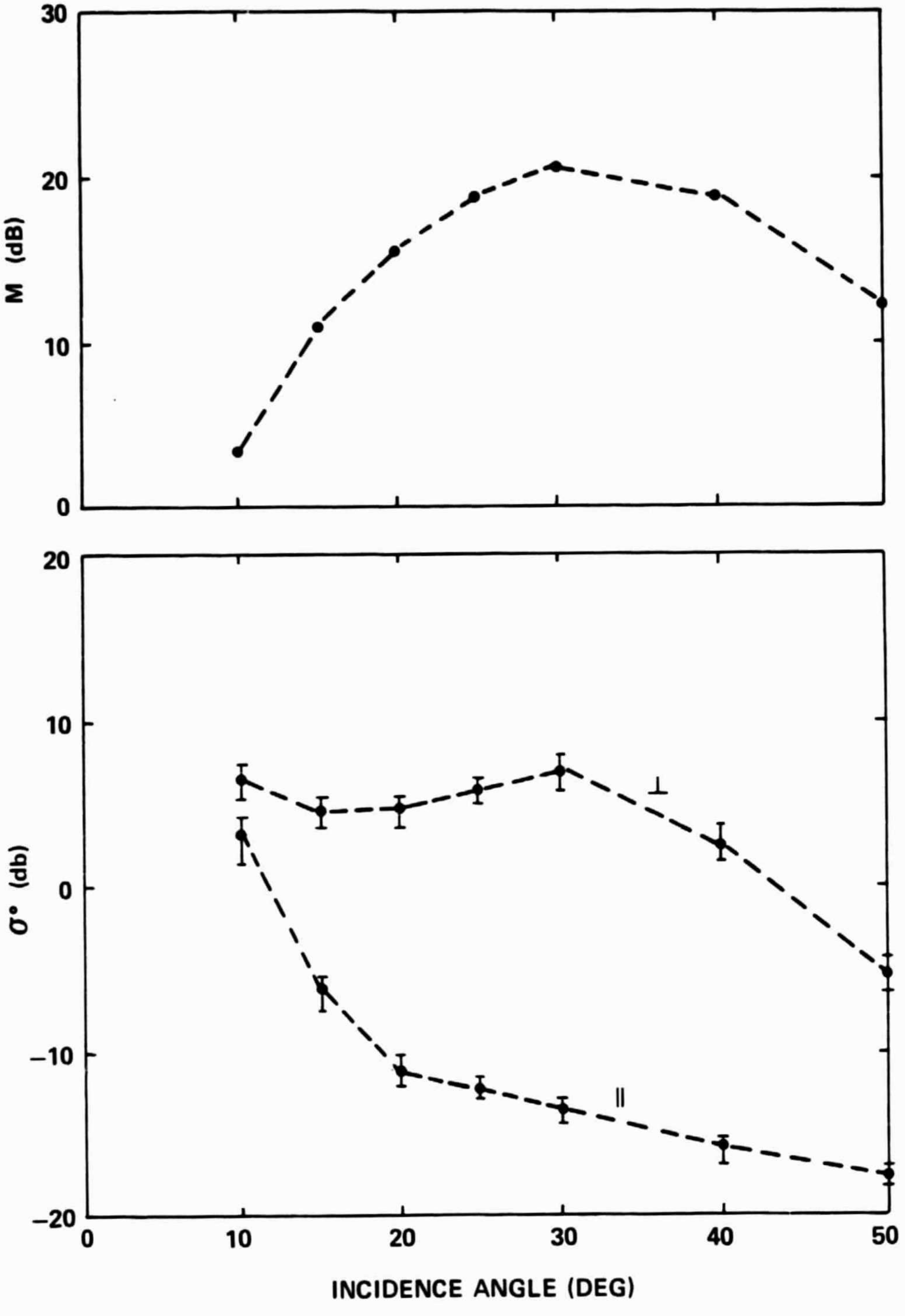
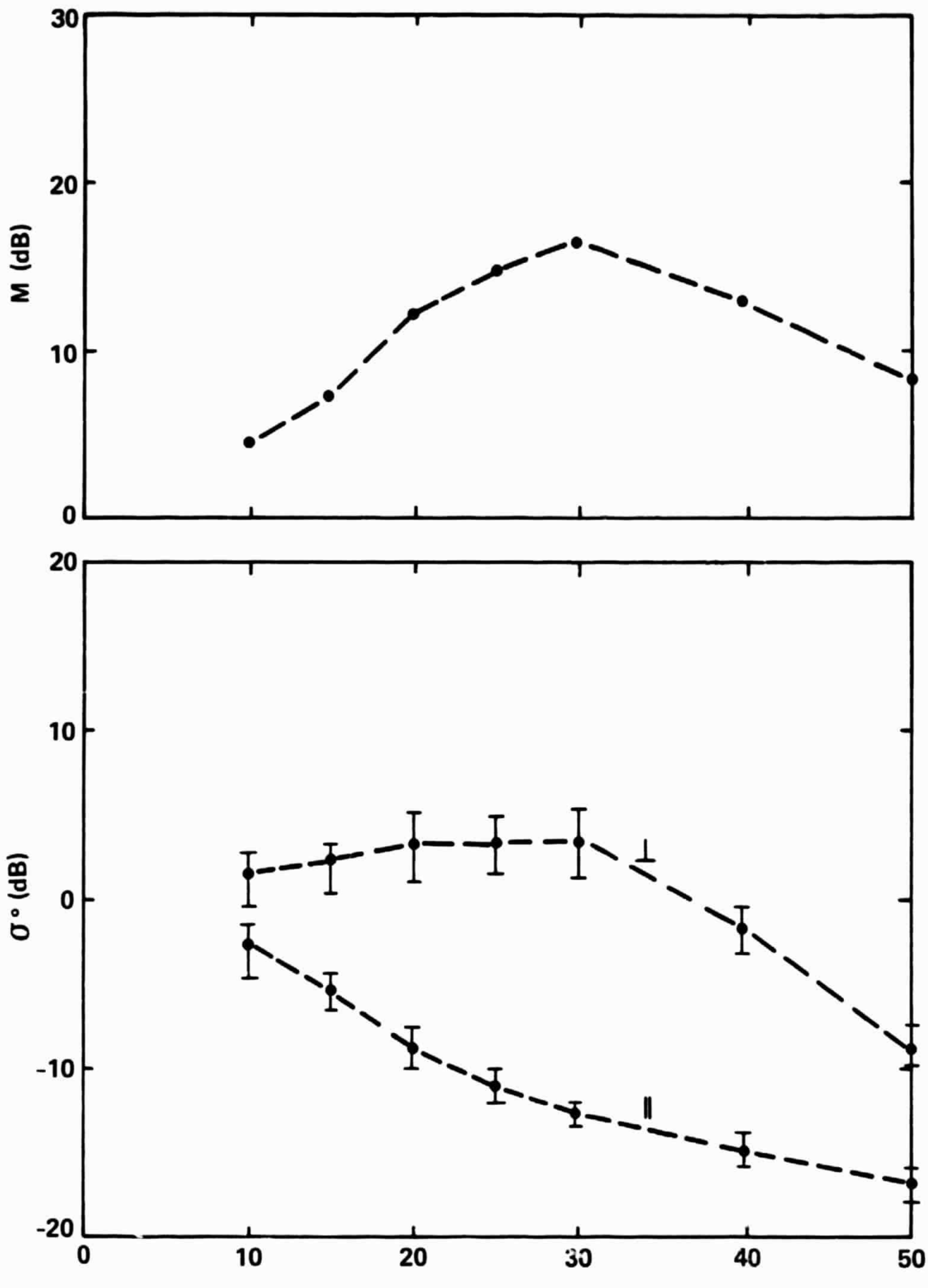


(a) L-band VV polarization.

Figure 21.- Results of measurements at Prairie View test site, September 15 through 17, 1980.



(b) C-band VV polarization.

Figure 21.- Continued.

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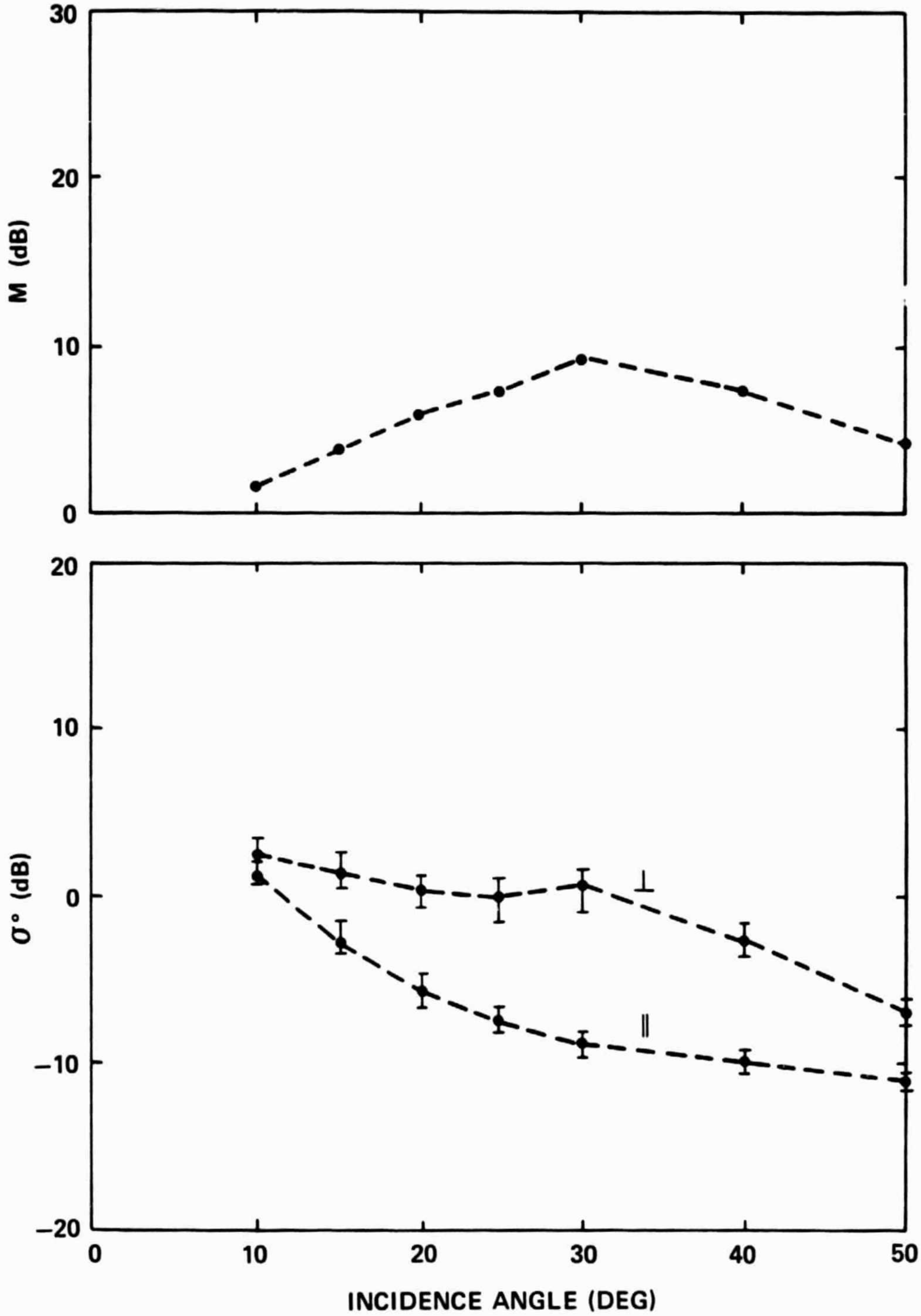
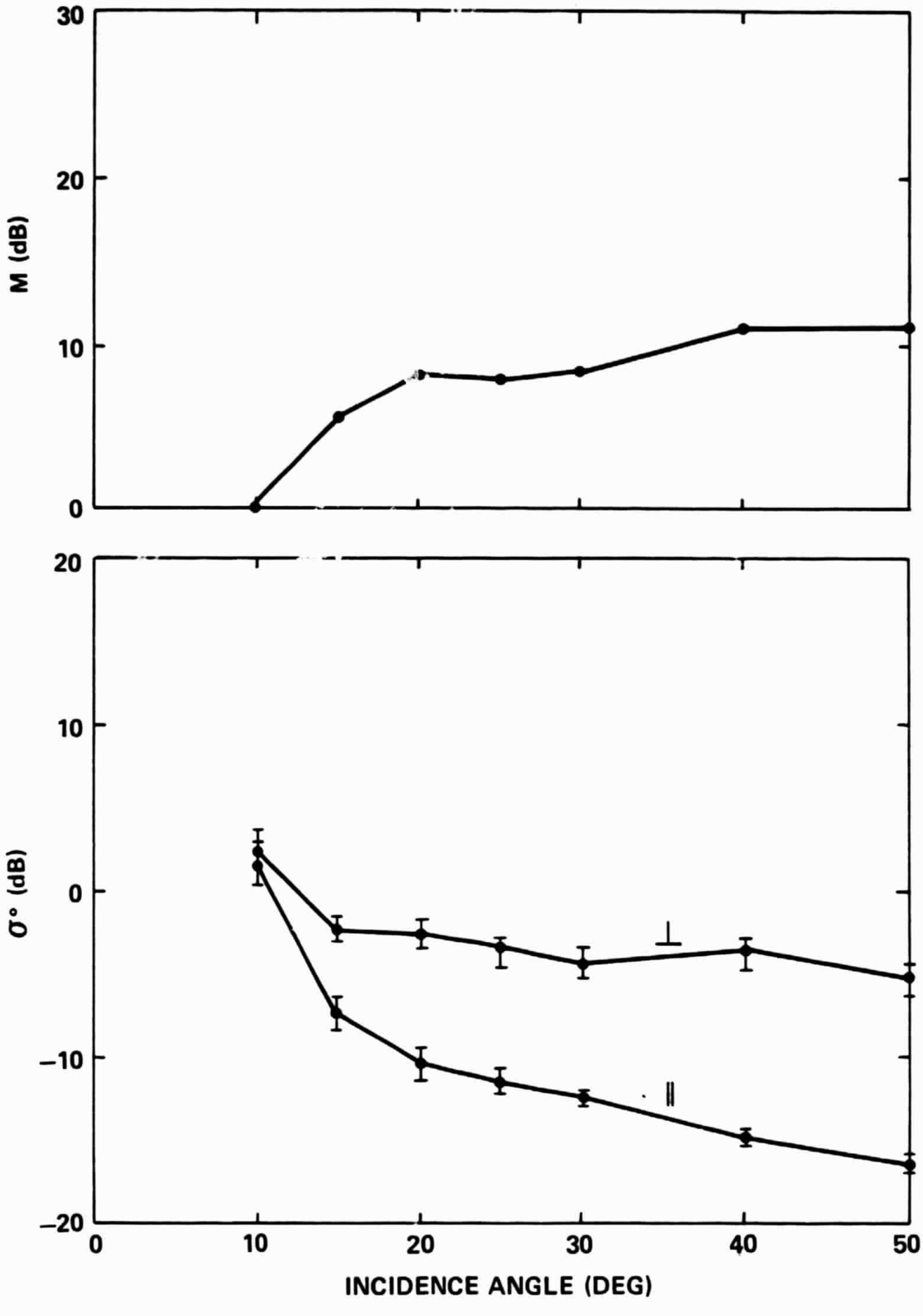


(c) Ku-band VV polarization.

Figure 21.- Concluded.



(a) L-band VV polarization.

Figure 22.- Results of measurements at Prairie View test site, September 22 through 24, 1980.

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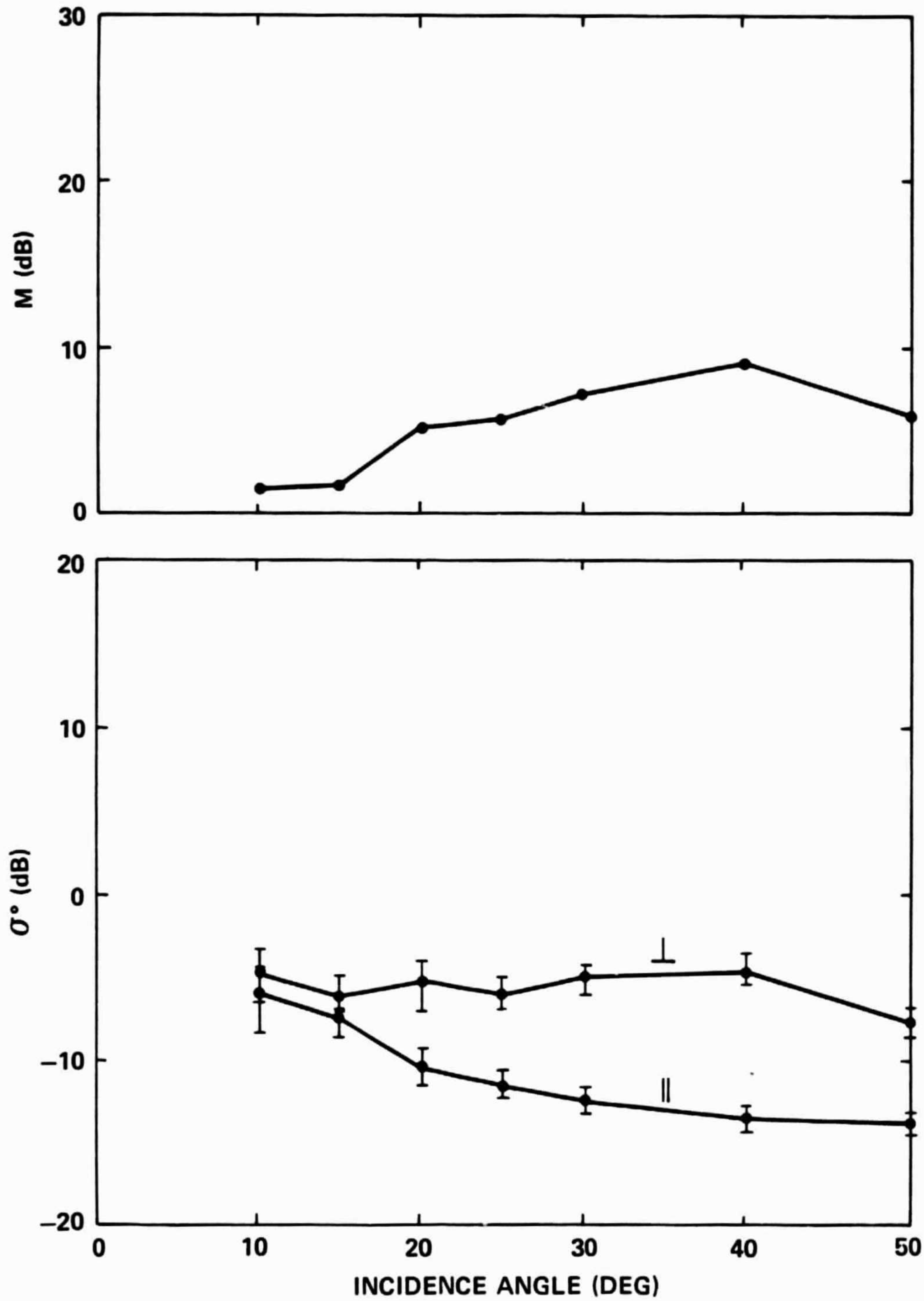
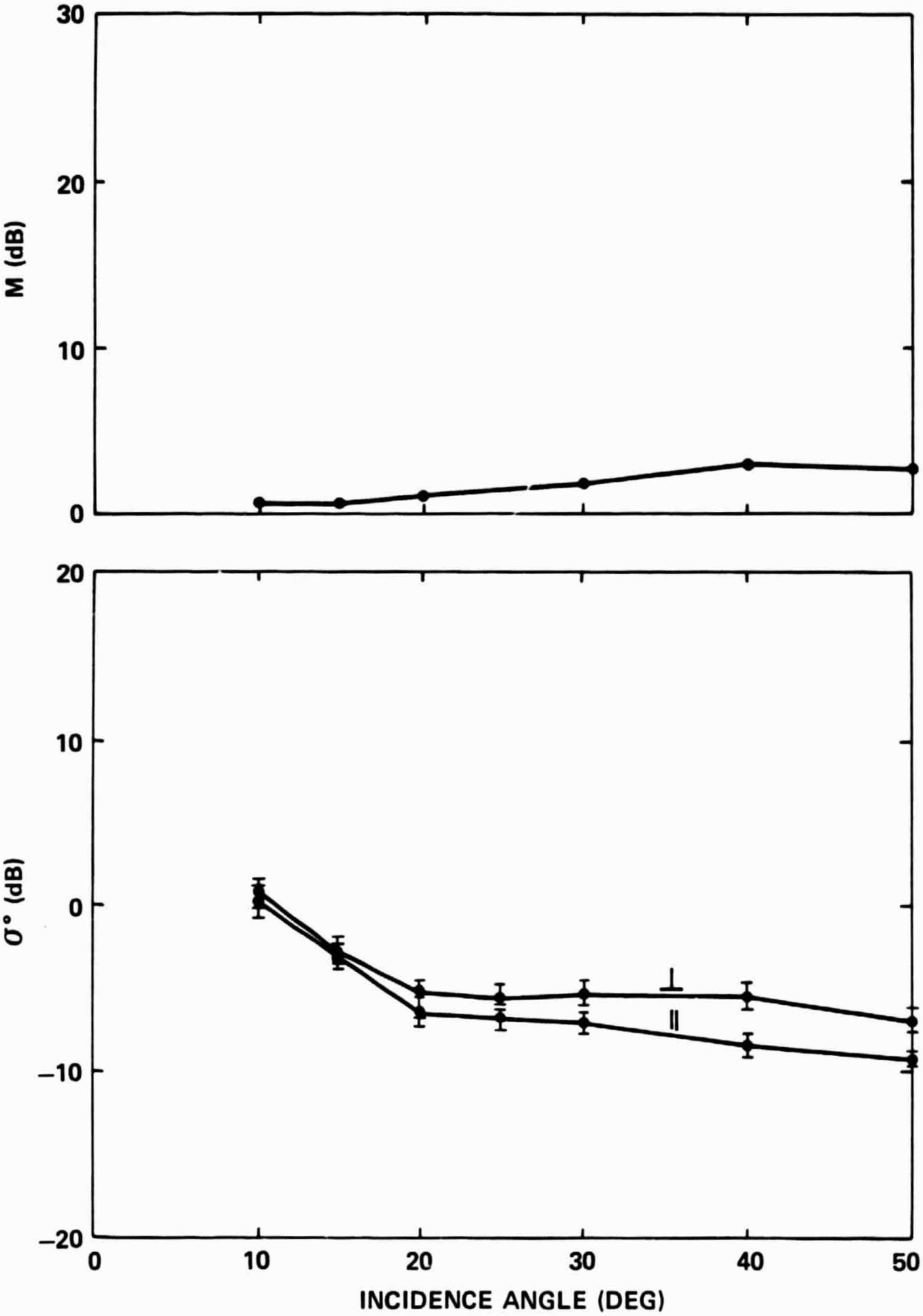


(b) C-band VV polarization.

Figure 22.- Continued.



(c) Ku-band VV polarization.

Figure 22.- Concluded.

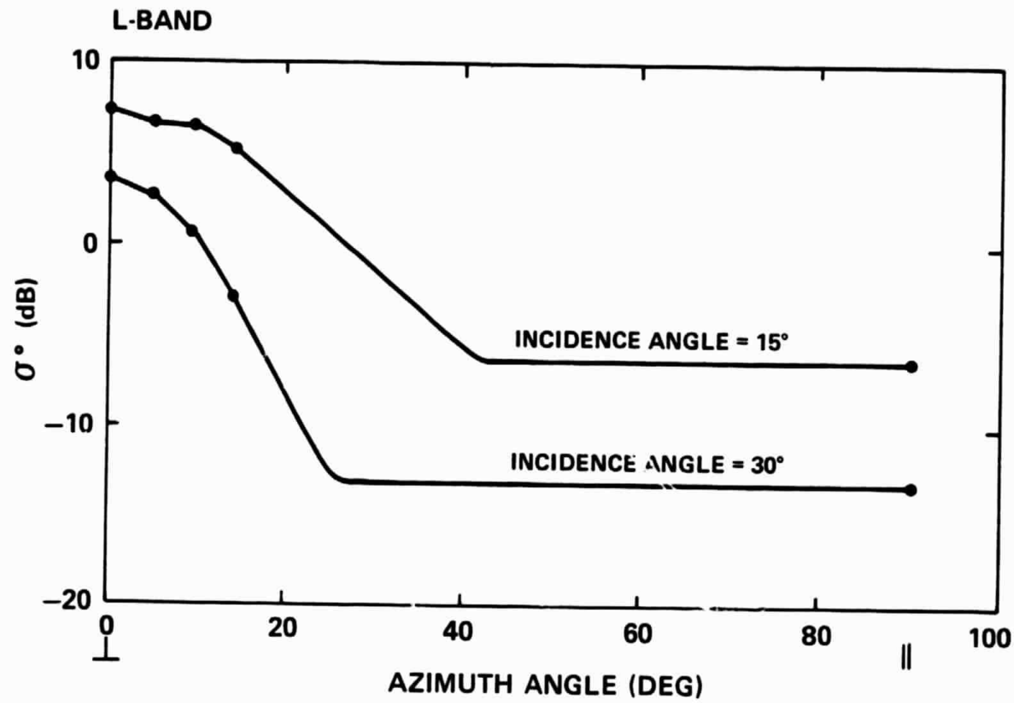
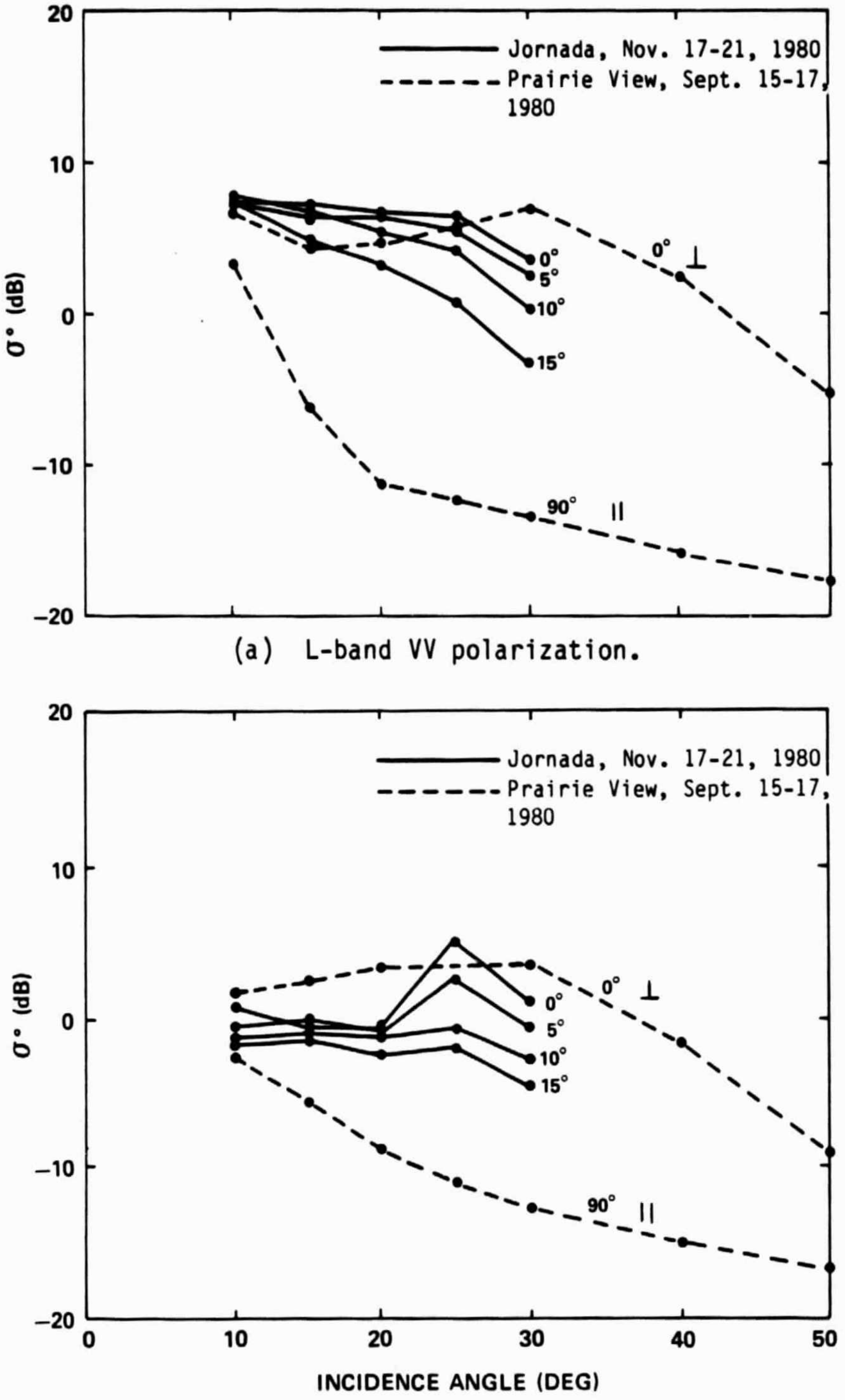


Figure 23.- Results of measurements at Jornada test site in November 1980: Azimuthal angle effects for L-band VV polarization.



(a) L-band VV polarization.

(b) C-band VV polarization.

Figure 24.- Results of measurements at Jornada test site in November 1980 compared to those at Prairie View test site.

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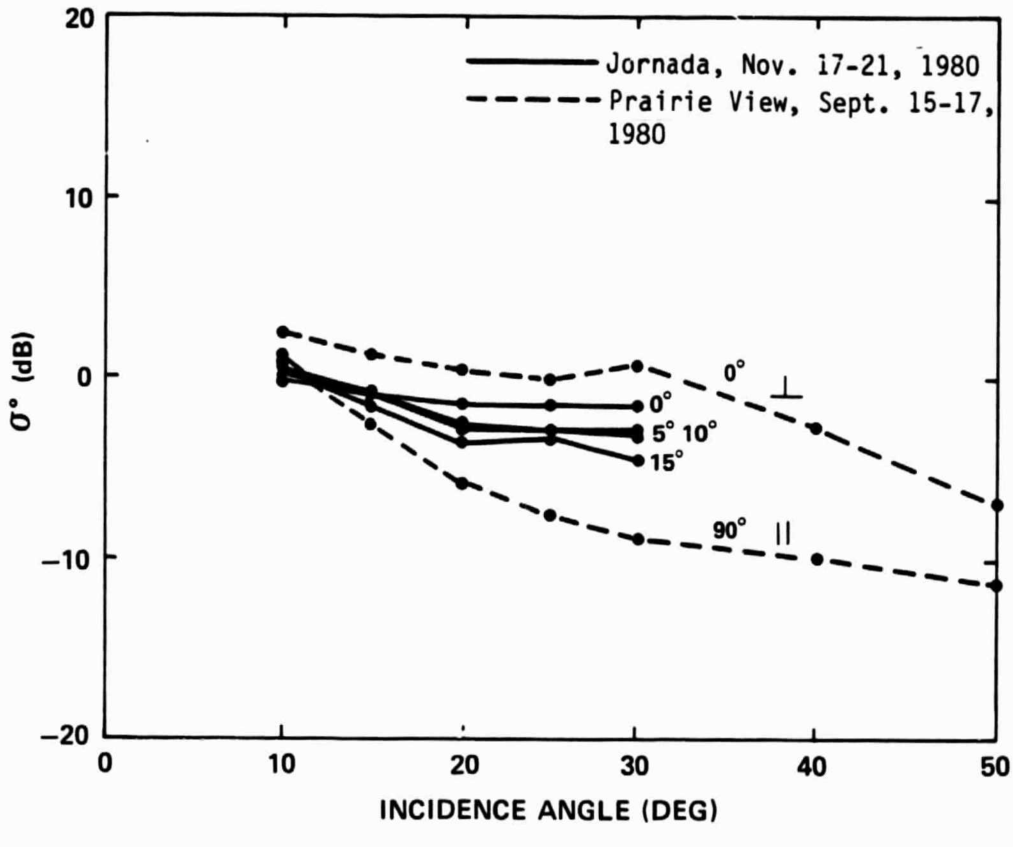

(c) Ku-band VV polarization.

Figure 24.- Concluded.

radar data will hold and that the sensitivity of cross-polarized radar data to soil moisture will be sufficient to provide information usable for crop applications. The cross-polarized configuration, if adopted, presents a design problem to SAR engineers, since the absolute level of backscatter is about one order of magnitude lower for cross-polarization than for like polarization when all other variables remain the same. This places a severe requirement on transmitted power from the satellite system. This problem, to be addressed in several experiments in FY 1982 and beyond, represents a critical question in the area of radar applications for soil moisture.

It has been generally believed that row direction would be important only for the kinds of row structure found in irrigated fields, especially those where furrow irrigation is used. Recent unpublished results by the lead author, however, indicate that the row-direction effect at C-band HH at an incidence angle of 10° is about 8 dB through mature stands of corn and soybeans in a particular area (Webster County, Iowa) where no irrigated fields exist. Thus, the problem of row direction appears to be more general and must be dealt with whenever remote sensing of soil moisture is employed, in both irrigated and nonirrigated areas.

5.4 MODIFICATION OF THE GROUND SCATTEROMETER SYSTEM

A portion of the FY 1981 SM project budget was used to make modifications on the GSS (fig. 25). The purpose of the modifications is threefold: (1) to enable the GSS to make more time-efficient measurements, (2) to improve the antenna and receiver characteristics so that cross-polarization measurements can be made, and (3) to add an additional frequency capability X-band (9.5 GHz) to the existing three frequencies - Ku-band (13.3 GHz), C-band (4.75 GHz), and L-band (1.6 GHz).

In order to increase GSS time efficiency, a new controller (HP-9825) has been added to the system to automate the sampling of the returned power for the backscatter calculation.

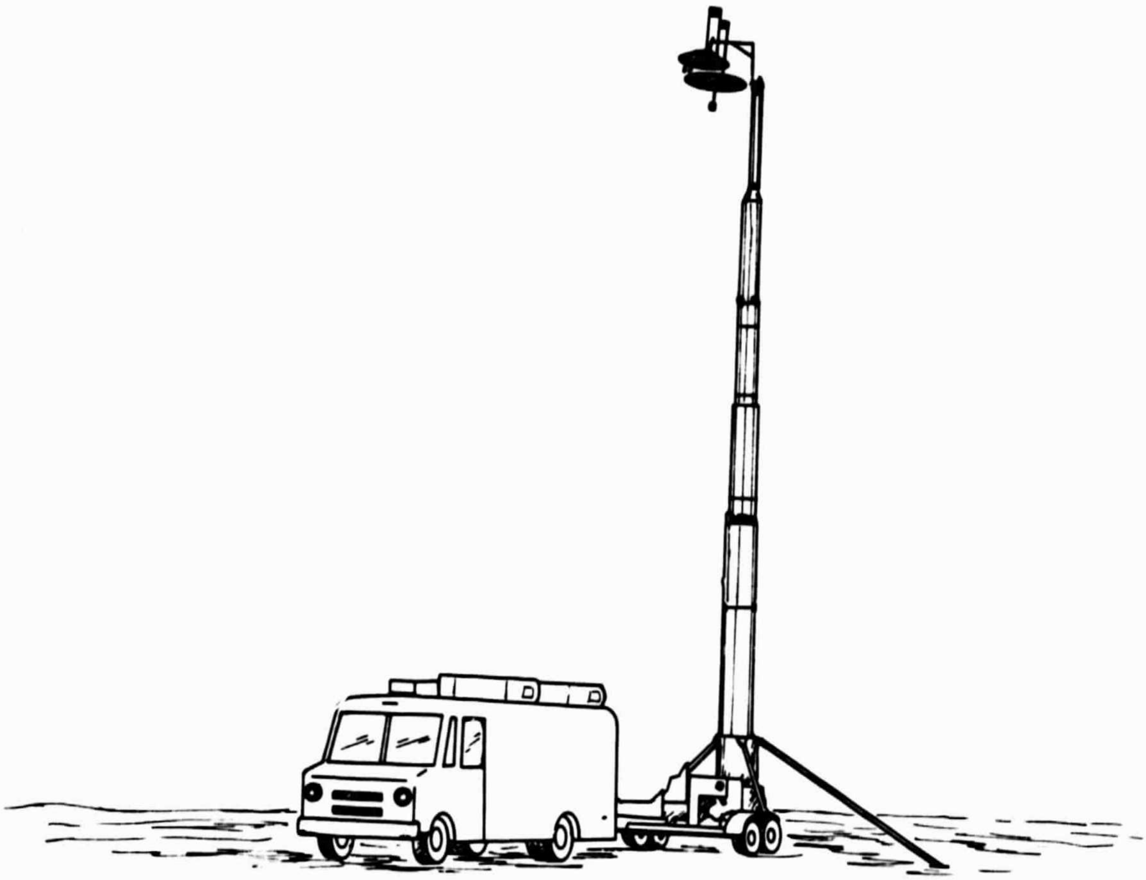

Figure 25.- The NASA/JSC Ground Scatterometer System.

New radiofrequency (rf) amplifiers and switching circuitry, currently being added, will improve signal-to-noise ratio values and will allow cross-polarization measurements to be made. Electronic switching is being added so that switching between transmit/receive polarization combinations (HH, HV, VH, and VV) for the different frequencies can be done more quickly and with improved measurement repeatability. The necessary hardware has been ordered.

To provide additional frequency capability, a new X-band transmitter and receiver are being added. Also, the horn antennas for the Ku-band are being replaced by dish antennas. After these steps are completed, the four separate frequencies will be operating through two pairs of dish antennas (X-band with Ku-band and C-band with L-band), providing dual-frequency and dual-polarization capabilities with each antenna pair. The L- and C-band antenna pair is getting new antenna feeds. The new antennas and antenna feeds are on order.

Several benefits have resulted from these modifications. Before the modification involving the computer/controller, the real-time calculation utilized a digital voltmeter (DVM) and spectrum analyzer. Computing backscatter required a manual operator with a thorough knowledge of both the scan rate of the analyzer and the sampling rate of the DVM. Not only has elimination of the DVM and analyzer reduced calculation uncertainties, but elimination of the manual operator inputs has reduced human error and fatigue. Consequently, data gathering can now occur over a continuous 48-hr period. The computer/controller uses a frequency synthesizer (±0.1 Hz) with a new analyzer; this increases accuracy and time efficiency. The new rf amplifiers will improve signal-to-noise ratios, allowing cross-polarization measurements to be taken. The switching circuitry will allow switching of both frequency and polarization, while the new X-band scatterometer transmitter and receiver will assist in the calibration of the X-band SAR from a known ground scene.

In summary, the electrical design has been completed, the hardware ordered, and the mechanical design is underway.

5.5 PREPROCESSING OF AGRICULTURAL SOIL MOISTURE EXPERIMENT DATA

The AIRP completed the preprocessing of the aircraft data acquired on July 18, 20, 21, and 22 and on August 8, 9, and 11, 1978, over the Colby (Kansas) test site. The last set of preprocessed data from the radar scatterometers, microwave radiometers, and infrared radiometers was sent to the ASME investigators and NASA/GSFC on February 29, 1981. In the preprocessing operations performed by the ESD in Building 15 at NASA/JSC, the original pulse-code-modulated analog data recorded on the aircraft during the aircraft flights were digitized, calibrated, and formatted into digital data on magnetic computer-compatible tape (CCT). In the case of scatterometer data, the data were preprocessed to form registered, nadir time correlated data sets. As a result, the radar scatterometer data can be handled by the investigator as if the backscattering coefficients were taken at the various angles (5° to 50° from nadir) at the same time - the time that the aircraft passes the ground point that is being viewed. Before preprocessing, the data taken from a given footprint area were taken at different times over about 7 sec as the fan shaped, aft-looking beam passed that area. Also, in the preprocessing, care was taken to adjust the Doppler shift interval used to ensure that the desired incidence angle was maintained in the face of aircraft roll and drift.

As a result of the preprocessing, ASME investigators possess 7 days of data taken over seven flight lines on each day. For each line, radar scatterometer data were acquired using seven combinations of frequency (wavelength) and polarization (P-band HH and HV, L-band HH and HV, C-band HH and HV, and Ku-band VV). For each scatterometer configuration, 10 angles of incidence were used (5° to 50° from nadir in steps of 5°). For each flight line, microwave radiometer data were acquired at L-, C-, X-, and Ku-bands. Either nadir-looking or off-nadir (either 40° or 50° for the X-band Passive Microwave Imaging System) microwave radiometer data were acquired. In some cases, lines 3 and 4, both nadir and off-nadir data were preprocessed. In addition, infrared radiometer data (nadir-looking) were taken on each line. Finally, photography was taken at high altitudes and low altitudes (1500 and 1000 ft above the ground, respectively). Soil moisture conditions ranged from very dry to very wet (in some cases above field capacity) during the course of the experiment. The Colby test site is shown in

figure 26. During the experiment, 43 fields received attention so far as the ground-truth sampling was concerned. The fields chosen are indicated in table 1. Table 2 shows the actual pattern of sampling by field and by day. The sampling pattern used within the fields is shown in figure 27.

In FY 1981, several reports were published by Lockheed-EMSCO that dealt with various aspects of the ASME ground truth. A report by Arya (1981) gave the hydrological properties of the Colby area soils.

To aid investigators in the location of aircraft sensor footprints during flights, the NASA/JSC Cartographic Technology Laboratory prepared controlled mosaics of each flight line, using high-altitude photography. Then, low-altitude photography was used to locate the center point [principal point (PP)] of each photograph on the controlled mosaic. The position of the PP is shown on an acetate overlay at the same scale as the controlled mosaic. The necessary acetate overlays showing the positions of the Zeiss and Hasselblad photography were completed by Lockheed-EMSCO in FY 1981 and sent to all ASME investigators and to NASA/GSFC.

5.6 DEVELOPMENT OF PROCESSING SOFTWARE PACKAGES FOR ASME DATA

As one of the ASME investigators, the NASA/JSC and Lockheed-EMSCO soil moisture study team will be analyzing the data in FY 1982. In preparation for this activity, Lockheed-EMSCO developed several software packages to enable one to locate accurately the position of each sensor footprint in the fields of interest in a ground-based coordinate system. A software package for each of the major systems (scatterometer, microwave radiometer, and infrared radiometer) on the aircraft has been developed. The software packages were developed and documented by Richter (June 1981 and Sept. 1981). The software packages are designed to be as automatic as possible in order to facilitate use and to ensure objectivity. Each package calculates the actual ground track of the aircraft by using the aircraft navigation data recorded onboard the aircraft during the time that sensor data are acquired along a flight line. These data, available every 0.5 sec, consist of aircraft heading, roll, drift, air speed, radar altitude above ground, and pitch. Since the sensor geometry (azimuth and nadir angle

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TABLE 1.- SOIL TYPE[a] AND CROP FOR THE TEST FIELDS

Field no.	Soil type[b]	Crop[c]	Field no.	Soil type[b]	Crop[c]
1	B	Corn	28	A	Corn
2	C	Corn	29	B	Wheat
3	B	Corn	30	B	Wheat
4	B	Wheat	31	B	Milo
5	B	Pasture	34	C, E	Milo
6	B	Fallow	37	B, E	Corn
7	B	Wheat	38	B	Wheat
8	A	Pasture	39	A	Milo
9	B	Fallow	40	B	Corn
10	A	Wheat	43	C	Fallow
11	A	Wheat	44	A	Wheat
12	A	Fallow	45	A	Fallow
13	A	Fallow	46	B	Wheat
14	B	Pasture	47	B, F	Wheat
19	A, D	Corn	49	A	Fallow
20	A, D	Corn	50	A	Fallow
21	A, D	Corn	52	B, E	Fallow
22	A	Corn	53	A	Wheat
24	B	Milo	54	A	Fallow
25	A	Wheat	55	C	Corn
26	B	Corn	56	B	Fallow
27	C	Wheat			

[a]These data were taken from an unpublished soils map provided by the USDA Soil Conservation Service in Colby.

[b]The following notations are used in this column.

A _ Keith silt loam, 0 percent to 1 percent slope.
B _ Keith silt loam, 0 percent to 1 percent slope.
C _ Keith silt loam, 1 percent to 3 percent slope.
D _ Richfield silty clay loam.
E _ Goshen silty loam, 1 percent to 3 percent slope (eroded).

[c]All corn fields were irrigated.

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TABLE 2.- SOIL MOISTURE SAMPLING ACTIVITY BY FIELD AND DAY[a]

Field no.	Julian day							
	199	200	201	202	203	220	221	223
1	—	—	X	X	X	P	—	—
2	X	—	X	X	C	X	X	P
3	X	—	X	X	P	X	X	X
4	X	—	X	X	X	X	X	X
5	C	—	X	X	X	X	X	X
6	X	—	X	X	X	X	X	X
7	X	—	X	X	X	X	X	X
8	C	—	X	X	X	X	X	X
9	X	—	X	X	X	X	X	X
10	X	—	X	X	X	X	X	X
11	X	—	X	X	X	X	X	X
12	X	—	X	X	X	X	X	X
13	X	—	X	X	X	X	X	X
14	X	—	X	X	X	X	X	X
19	X	—	—	C	C	—	—	—
20	X	—	X	P	P	—	—	—
21	X	—	X	P	P	—	—	—
22	X	—	—	—	—	—	—	—
24	X	—	—	—	—	X	X	—
25	X	—	X	X	X	X	—	X
26	X	—	X	P	P	P	—	—
27	X	—	X	X	X	X	X	X
28	—	C	—	—	—	—	P	P
29	—	C	—	P	P	P	X	X
30	—	C	—	—	P	P	X	X
31	—	C	—	—	P	X	—	—
34	C	—	—	—	C	—	X	—
37	—	C	—	C	P	X	X	X
38	—	C	C	C	—	P	X	X
39	P	—	X	—	X	X	X	X
40	X	—	—	—	C	X	P	X
43	—	C	—	—	P	X	X	X
44	X	C	X	X	X	—	P	—
45	—	—	—	—	—	X	X	X
46	X	—	X	X	X	X	X	X
47	X	—	X	—	X	X	X	X
49	X	—	X	X	X	X	X	X
50	X	—	X	X	C	X	X	X
52	X	—	X	X	X	X	X	X
53	X	—	X	X	X	X	X	—
54	X	—	X	X	X	X	X	P
55	X	—	X	X	X	—	—	—
56	—	—	—	—	—	P	P	P

[a]The following notations are used in the table:

X: Field well sampled (90 to 148 samples).
P: Partial data set (20 to 90 samples).
C: Abbreviated data set (usually core samples only; up to 20 samples).
—: No data available.

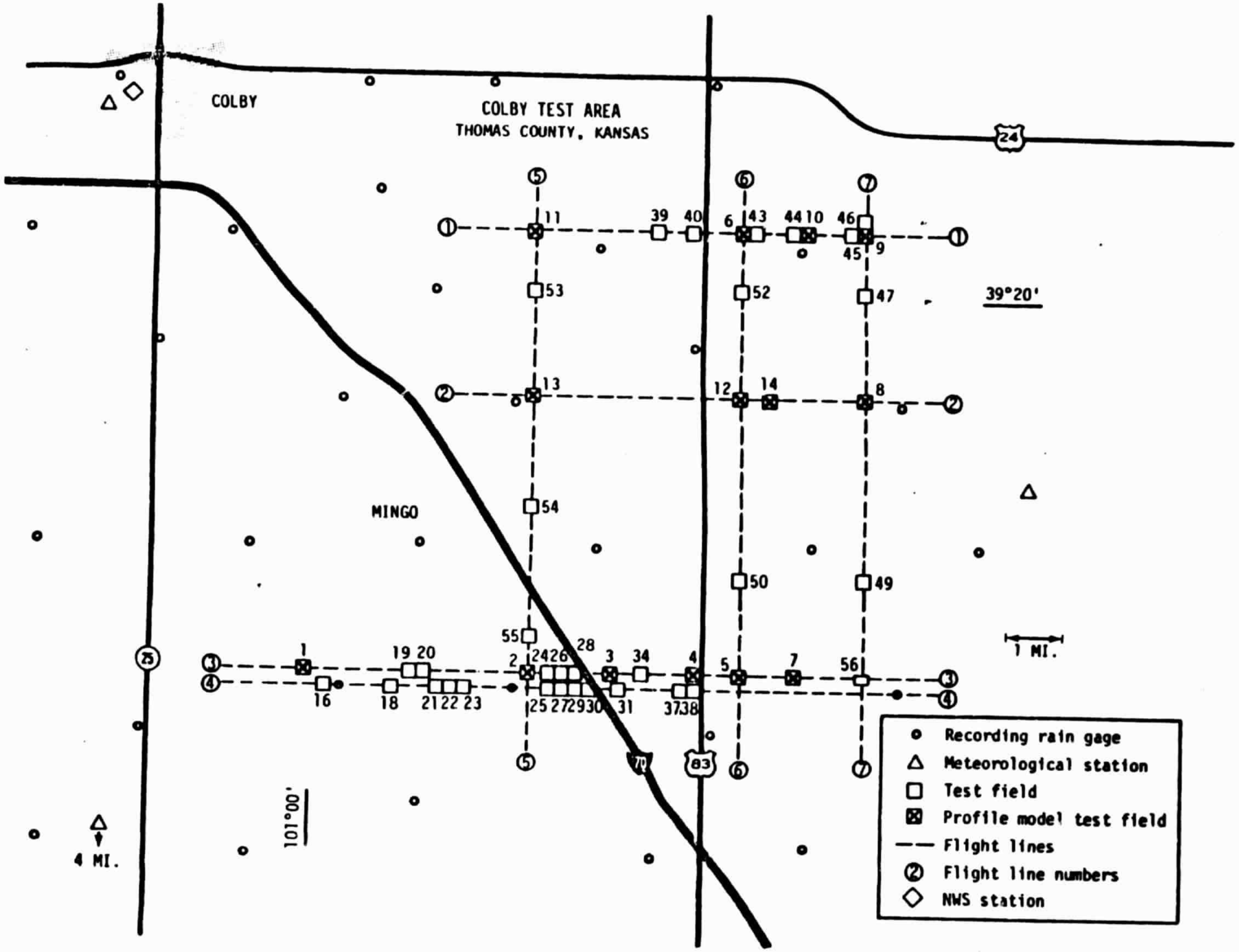
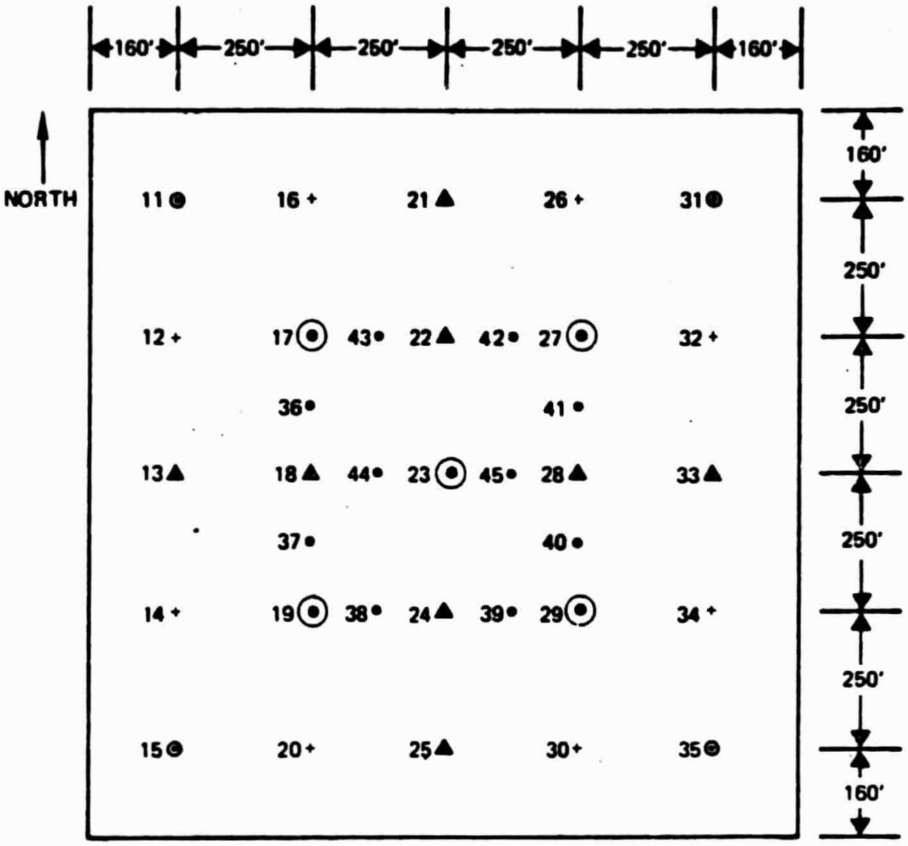


Figure 26.- Locations of the 43 test fields used for ground-truth data acquisition.



Symbol	Sample depths, cm	No. of locations	No. of samples per location	Total
•	0-1, 1-2	10	2	20
+	0-1, 1-2, 2-5	8	3	24
▲	0-1, 1-2, 2-5, 5-9, 9-15	8	5	40
⊙	0-1, 1-2, 2-5, 5-9, 9-15, 0-15	4	6	24
⦿	0-1, 1-2, 2-5, 5-9, 9-15, 0-15, 15-30, 30-45	5	8	40
Total samples				148

Figure 27.- Sample locations and depth intervals sampled at the various locations.

from aircraft nadir, not true nadir) is known, the location of the sensor footprint (i.e., the area viewed during a measurement) can be calculated. The results of the calculation are given in a tabulation (data file) and as a printer plot using the same scale as the controlled mosaics discussed above. A check is made of the agreement between the position of the calculated footprints and the position of the PP's of the low-altitude photography. Figure 28 shows an example of the printer plot overlaid on the PP plots and the controlled mosaic. Thus far, the agreement between the calculated footprint positions and the photographic positions has been excellent.

Another software package has been developed to display the footprint locations on an individual field map (produced by the line printer at a larger scale than that used in figure 28). Shown on the same display are the locations, location numbers, and values of the surface-zone soil moisture measurements made on that field on the day of the flight. Also, a strip-chart-like plot is made of the sensor readings during the time of the flight over the field at the left of the field plot. An example of this plot is given in figure 29.

The purpose of processing the data in the manner described above is to allow an analyst to associate certain subsets of ground-truth data with sensor measurements made for a particular sensor footprint area. Thus, sets of observations can be constructed that give the sensor and ground-truth measurements made on or near the same small area (sensor footprint). Other investigators in the ASME are comparing field averages of remote-sensor data to field averages of ground-truth data. In many cases, it is not appropriate to compare these field averages, since the areas used in the averaging process are not equal. The remote-sensor data are taken over a strip in the field; the ground-truth data are taken over the whole field, weighted toward the center of the field. The procedure that is being followed at NASA/JSC will reduce the bias.

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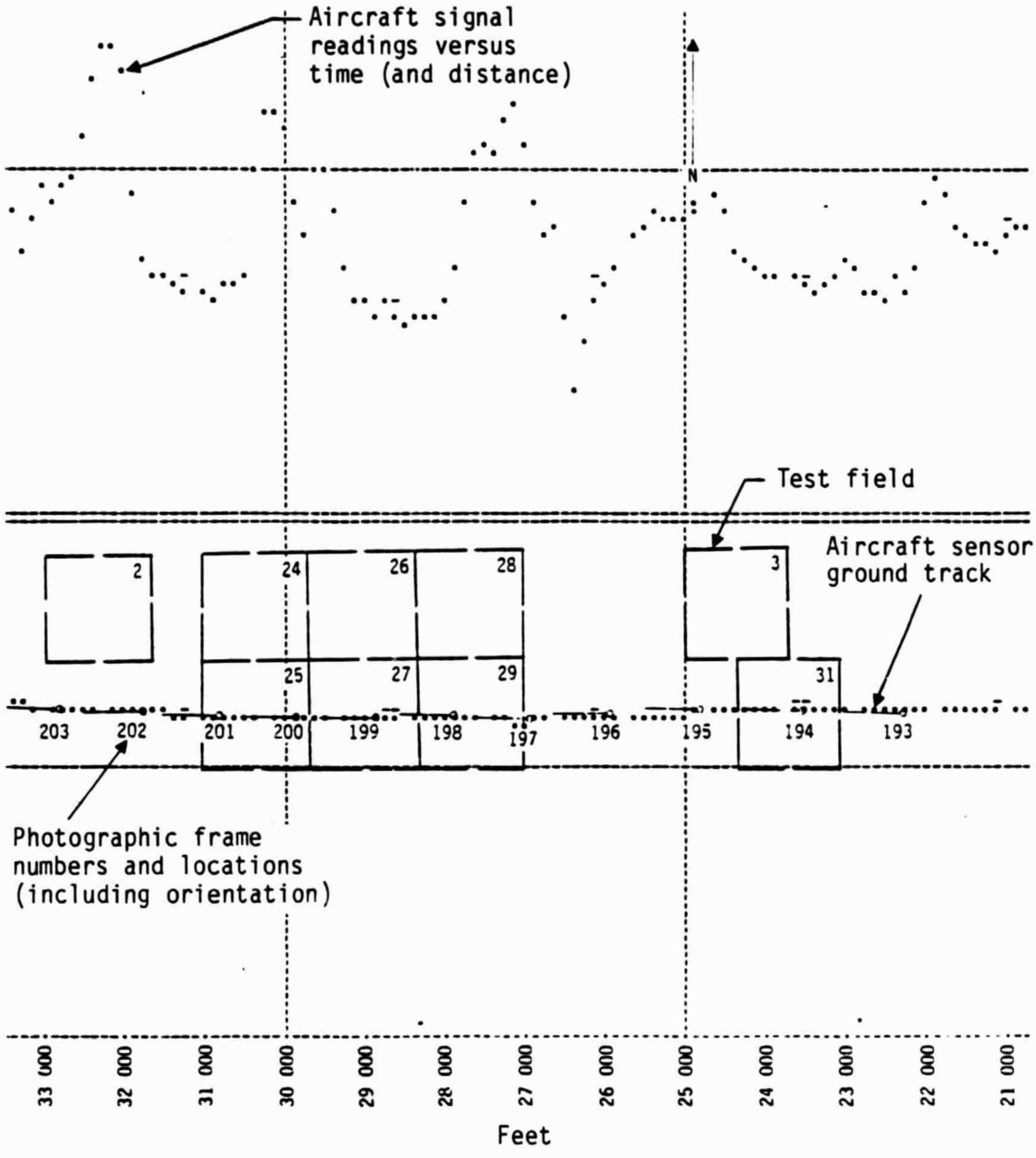

Figure 28.- Illustration of the plot of the aircraft's ground track with overlays indicating the photographic position and field boundaries.

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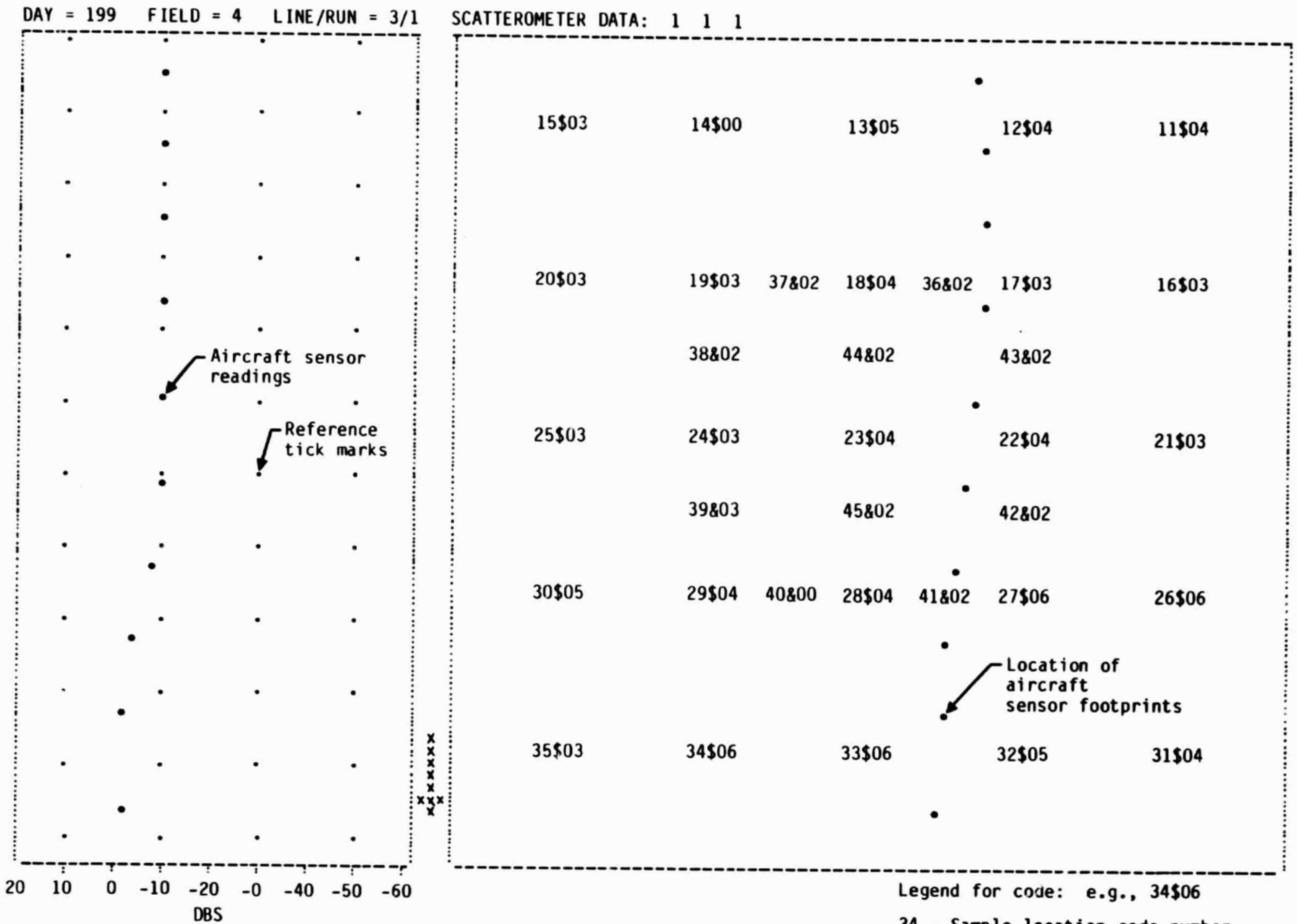

DECORRELATION DISTANCES ARE: 166 170 173 177 180
183 186 189 192 195

Legend for code: e.g., 34$06

34 - Sample location code number
06 - 6% soil moisture content
$ - Depth interval: 2 to 5 cm
& - Depth interval: 1 to 2 cm

Figure 29.- Combined plot of aircraft and ground-truth data for a sample field.

5.7 HYPOTHESIS TESTING OF CANDIDATE SOIL MOISTURE ALGORITHMS

A plan for the testing and evaluation of remote-sensor-based soil moisture prediction models has been developed by Lockheed-EMSCO personnel. The objectives set forth under this plan are as follows:

- Determine which of the candidate soil moisture algorithms has the highest overall accuracy.
- Determine the effect of row structure upon the performance of the algorithms.
- Determine the effect of ground cover upon the performance of the algorithms.
- Determine if the performance of the algorithms is soil moisture dependent.
- Determine if the performance of the algorithms is a function of the time of ground data collection versus the time of overflight of the sensors.
- Determine if the accuracy of direct field-level estimates differs statistically from aggregated field-level estimates.
- Determine what units of measurement result in the highest prediction accuracy.

The measure of "goodness" for each algorithm will be

Soil moisture predicted - Soil moisture measured

The statistical model to be employed in the evaluation will be

$$d_{ijkr} = \mu + a_i + b_j + c_k + (ab)_{ij} + (ac)_{ik} + (bc)_{jk} + R_{1i}A_{ijkr} + R_{2i}B_{ijkr} + R_{3i}C_{ijkr} + e_{ijkr} \qquad (2)$$

where

d_{ijkr} = r^{th} measure of accuracy from algorithm i, row structure j, and ground cover k

μ = overall mean accuracy

a_i = effect of algorithm i

b_j = effect of row structure j

c_k = effect of ground cover k

$$\left.\begin{matrix}(ab)_{ij}\\(ac)_{ik}\\(bc)_{jk}\end{matrix}\right\} = \text{second-order interaction}$$

A_{ijkr} = soil moisture with regression coefficient R_{1i}

B_{ijkr} = time of ground data collection with regression coefficient R_{2i}

C_{ijkr} = time of overflight with regression coefficient R_{3i}

e_{ijkr} = random error

The specific hypotheses to be tested will be in conformance with the model and the restrictions of the data (Searle, 1971).

5.8 IMPROVED RADAR IMAGE SIMULATION MODEL FOR INVESTIGATING THE EFFECTS OF SPATIAL RESOLUTION ON SOIL MOISTURE SENSING

In the amended SM PIP, authorization was included to fund an effort by KU CRES to continue development of a procedure to simulate SAR images. The simulations are used as a tool to investigate the effects of spatial resolution by a candidate SAR system on the estimation of soil moisture condition. The effort had been funded by NASA/GSFC in prior fiscal years but had been dropped because of funding cuts. A contract was signed with KU CRES on August 15, 1981, for 6 months of work to improve the existing model approach. The main deficiency in the existing model, in the opinion of NASA/JSC, is the method by which soil moisture values are generated for the small areas (20 by 20 m) that are the basic drivers for the simulations. The simulation area, a 17.6- by 19.2-km (11- by 12-mile) area near KU CRES, encompasses a number of different soil types and land use categories. Models are chosen to predict the backscattering coefficient for a given sensor frequency and polarization combination as a function of land use type, soil moisture content, and local angle of incidence. (Local slope and sensor angle of incidence are taken into account.) This process is followed for each 20- by 20-m picture element (pixel) in the scene.

Then, the spatial resolution is degraded by various amounts, and an image is simulated accordingly. The degraded image data are then used in a simple algorithm to recover the soil moisture value as estimated from the image data. The input soil moisture and the estimated soil moisture contents do not agree; thus, an error is produced. The effects of spatial resolution are investigated by examination of the amount and distribution of the error generated. The process appears sound except in the way that the input soil moisture, or so-called "true" soil moisture, values are obtained: They are obtained through the use of a water budget model in which the water-holding capacity varies with soil type and the evaporation is constant for all soil types and land-cover types. The latter assumption is a gross oversimplification of reality. Under this assumption, bare fields and vegetated fields within the same soil type produce exactly the same soil moisture, and only changes in soil type can produce differences in soil moisture distribution in the area. Thus, the spatial distribution of the true soil moisture content is unrealistically smooth. The new contract calls for an improvement in the model by using differing soil moisture contents in fields having different land cover and by allowing a random variation of soil moisture even within a class (field). The conclusions of the earlier investigation were that relatively low-resolution radar (about 100 to 1000 m) would be sufficient for the remote sensing of soil moisture for such an area; however, the higher variability expected from the new modeling approach may produce a different conclusion.

5.9 DEVELOPMENT OF SOIL WATER CHARACTERISTIC MODEL

Soil moisture modeling and analyses of soil water processes require data relating soil water pressure to soil water content and hydraulic conductivity to either the soil water pressure or the soil water content. The former, commonly referred to as the soil moisture characteristic, not only is used in translating moisture gradients to hydraulic potential gradients in a flow system but also is an input for some hydraulic conductivity models.

Experimental determination of the soil moisture characteristic (using field or laboratory procedures) is tedious, time consuming, and expensive. An alternative to the experimental effort is the prediction of the soil moisture characteristic from routinely measured textural and structural soil properties. Of

the several existing models of the soil moisture characteristic, some describe the relationship of soil water pressure to water content by a power curve and distinguish between soils by empirical constants (Clapp and Hornberger, 1978); others relate the water content at specified soil water pressure to soil texture (percentage of sand, silt, and clay), organic matter, and bulk density, using multiple regression analyses (e.g., Gupta and Larson, 1979). Both of these approaches, however, lack the physical basis to account for the effects of grain-size distribution and packing characteristics of the medium. As a result, there is poor agreement between the models.

The Lockheed-EMSCO and NASA/JSC approach (Arya and Paris, 1981) is substantially physical. It distributes a given pore volume (hence the total volume of water) according to particle-size distribution of the soil and relates the pore radius to particle radius, number of particles, and packing characteristics of the medium. The pore radii are translated to equivalent pressures using the equation of capillarity. The inputs to this model are particle-size distribution curve, bulk density (natural state of packing), and particle density. (See figure 30 for an example of the input data.) The governing equations of the model are

$$V_{v_i} = (W_i/\rho_p)e \quad ; \quad i = 1,2,\cdots,n \tag{3}$$

$$e = (\rho_p - \rho_b)/\rho_b \tag{4}$$

$$\theta_{v_i} = \sum_{j=1}^{j=i} V_{v_j} \Big/ V_b \quad ; \quad i = 1,2,\cdots,n \tag{5}$$

$$V_b = 1/\rho_b \tag{6}$$

$$\bar{\theta}_{v_i} = \left(\theta_{v_i} + \theta_{v_{i+1}}\right)\Big/ 2 \tag{7}$$

$$r_i = R_i\left[4en_i^{(1-\alpha)}\Big/ 6\right]^{1/2} \tag{8}$$

$$n_i = 3W_i/4\rho_p\pi R_i^3 \tag{9}$$

$$\psi_i = 2\gamma\,\cos\delta/\rho_w g r_i \tag{10}$$

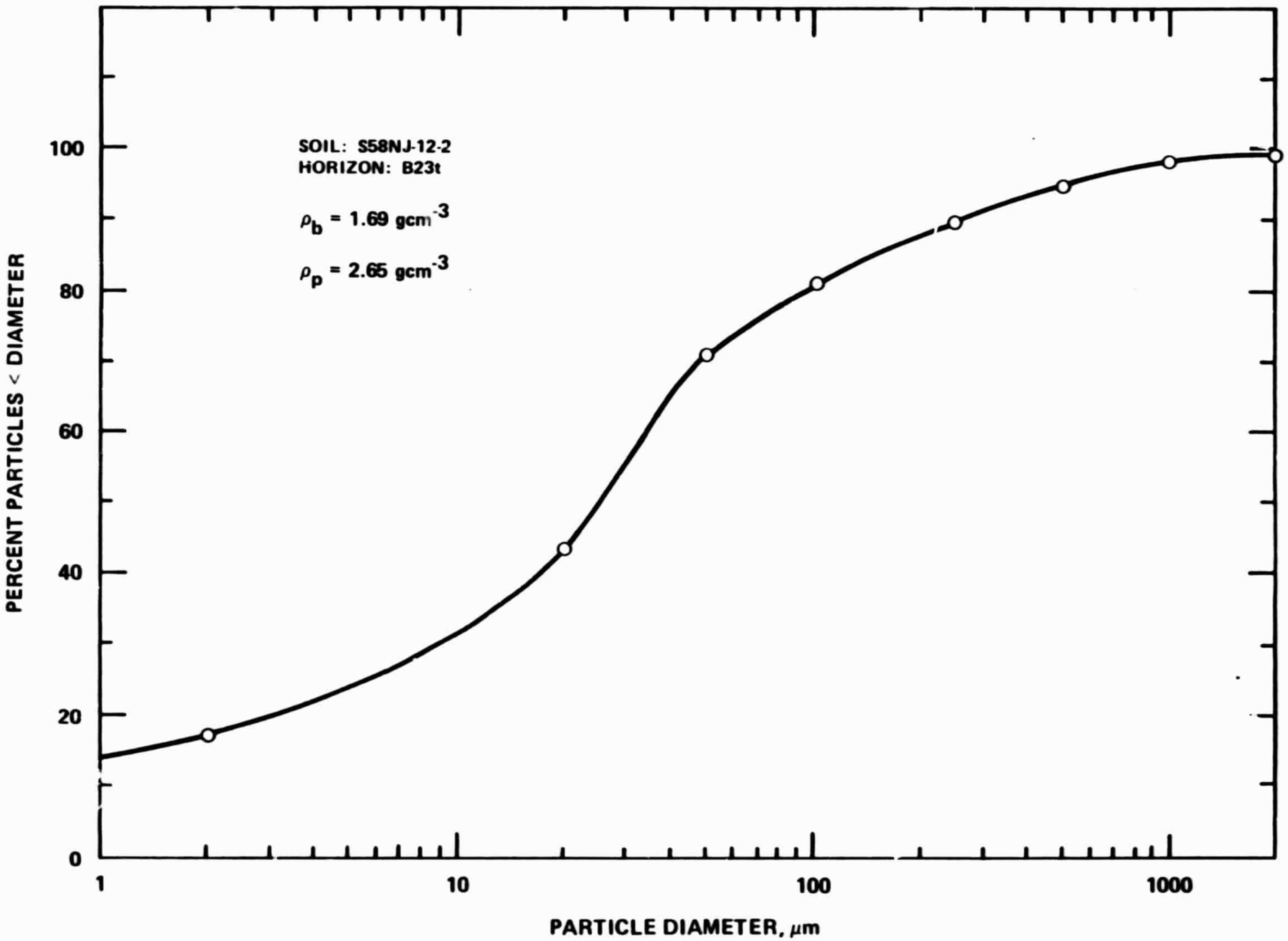

Figure 30.- Particle-size distribution, bulk density, and particle density for a New Jersey soil sample (from Soil Survey Investigations Report No. 26, 1974).

where

V_{v_i} = pore volume associated with the assemblage of particles in the i^{th} particle-size range

W_i = solid mass in the i^{th} particle-size range

ρ_p = particle density of the soil

e = void ratio; i.e., pore volume ÷ solid volume

ρ_b = bulk density of the soil in the natural state of packing

θ_{v_i} = volumetric water content when pores formed by particles in the first to the i^{th} particle-size range are filled with water

r_i = mean pore radius

R_i = mean particle radius

n_i = number of particles in the assemblage

α = empirical constant = 1.38

ψ_i = soil water pressure needed to empty the pores with radii larger than r_i

δ = contact angle between water meniscus and pore wall

ρ_w = density of water

g = acceleration due to gravity

γ = surface tension of water

Figure 31 compares the predicted and measured moisture characteristic data for a New Jersey soil sample (Soil Survey Investigations Report No. 26, 1974).

5.10 RELATIONSHIP BETWEEN SURFACE-ZONE SOIL MOISTURE AND SURFACE SOIL WATER FLUX (EVAPORATION AND INFILTRATION)

Evaporation and infiltration fluxes are important components in a soil moisture budget. Research is underway to develop algorithms which can predict these fluxes from frequent surface-zone soil moisture data obtainable by remote-sensing techniques.

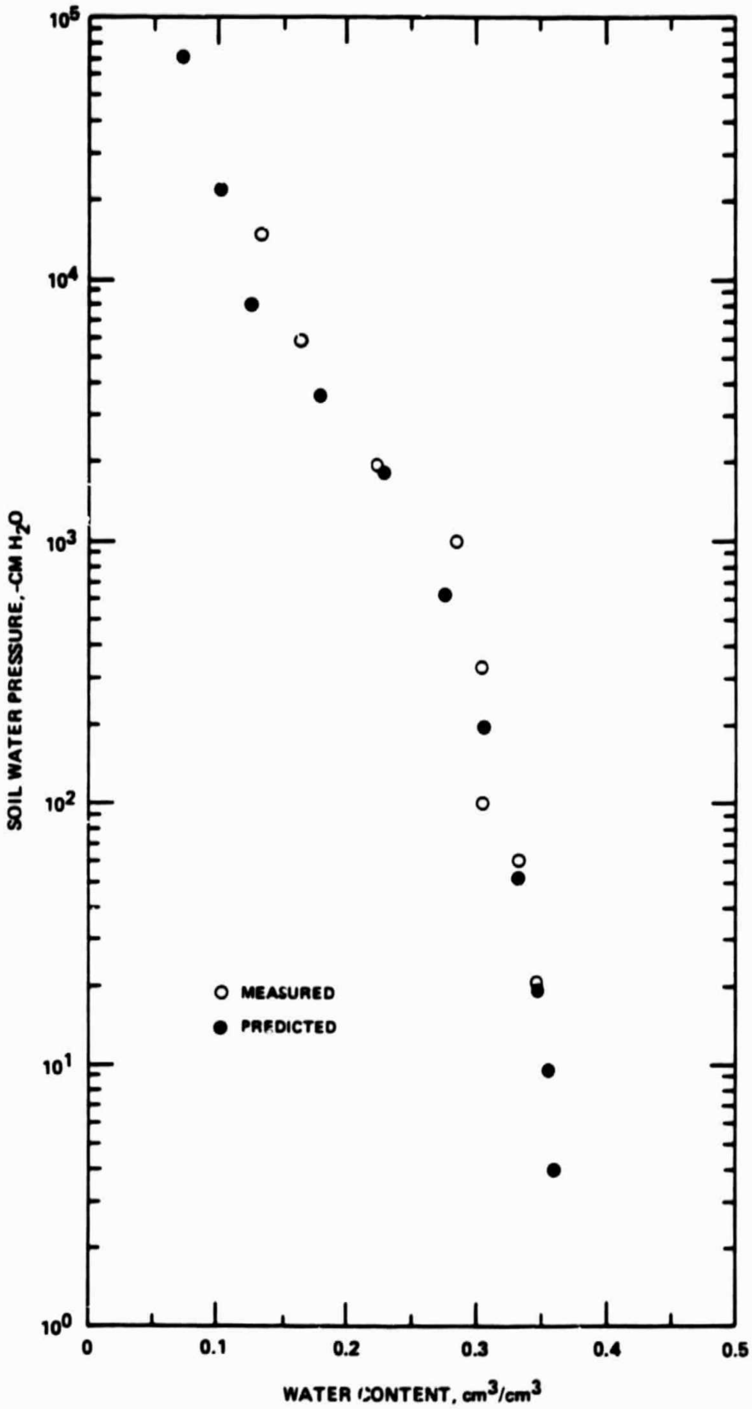

Figure 31.- A comparison of soil moisture characteristic predicted by Arya-Paris model with the laboratory-measured data for a New Jersey soil sample described in figure 30.

Preliminary results are based on a moisture balance of the surface zone in bare fields in the following form:

$$q_{z_0} = \int_{z_0}^{z_b} (\partial\theta/\partial t)dz + [K(\theta)\partial\Phi/\partial z]_{z_b} \quad (11)$$

where q_{z_0} is the surface flux, θ is the volumetric water content, t is the time, $K(\theta)$ is the hydraulic conductivity as a function of water content, Φ is the hydraulic potential, and z is the vertical depth coordinate taken positive upward. Subscripts 0 and b refer to the soil surface and the bottom of the surface zone, respectively.

The hydraulic potential Φ is given by

$$\Phi = \psi + z \quad (12)$$

where ψ is the soil water pressure.

The first term on the right side in equation (11) can be evaluated from frequent measurements of volumetric water content between the soil surface and the depth z_b. The second term, however, can be evaluated only if data are available on hydraulic conductivity, soil moisture characteristic, and moisture distribution in the surface zone.

Soil moisture characteristic data for a Keith silt loam soil (near Colby, Kansas) were computed by a modified Arya-Paris model (described in this report). The hydraulic conductivity was computed by Jackson's method (Jackson, 1972) using the soil moisture characteristic data as input.

An empirical approach was used to predict the moisture content of a fraction of the surface zone given the overall mean moisture content of the surface zone. A typical result is shown in figure 32. This approach provided two closely spaced data points which were assumed to be linearly connected. The two-point linear moisture profile was translated into a hydraulic potential profile using the moisture characteristic curve and equation (12). Thus, it was possible to approximate the hydraulic potential gradient in equation (11).

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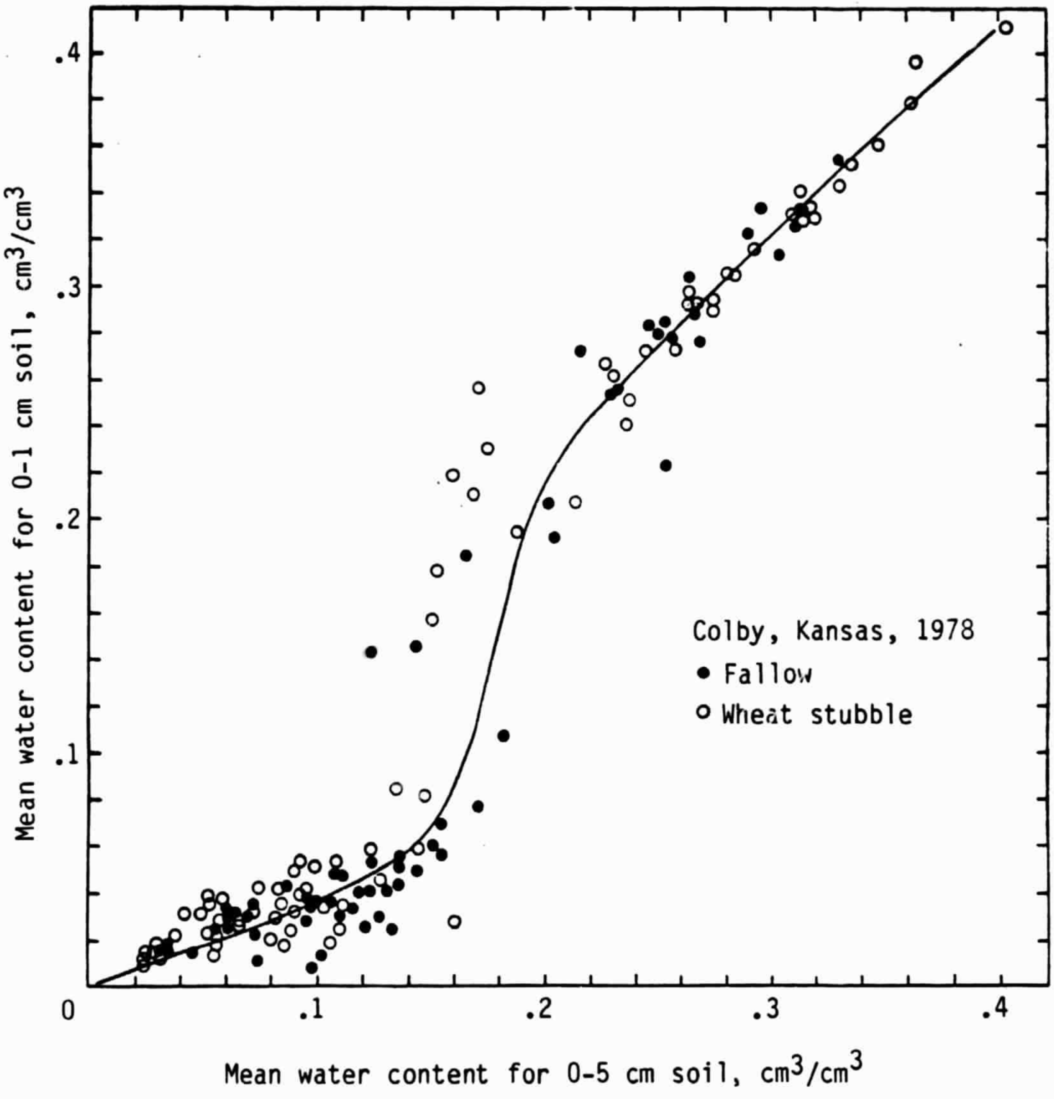

Figure 32.- Relationship between the moisture contents of 0- to 1-cm and 0- to 5-cm layers in Keith silt loam, Colby, Kansas.

Surface fluxes based on equation (11) and those predicted by the soil moisture model CONSERB (Van Bavel and Lascano, 1979) are compared in figure 33.

5.11 SOIL MOISTURE MODELING

Progress related to element 4, task 3, consisted mainly of comparative analyses and sensitivity studies of soil moisture profile models with the objectives of determining the model or models which were (1) best representative of the root-zone soil moisture changes, (2) capable of incorporating by program changes remotely sensed surface soil moisture data, and (3) relatively easy and inexpensive to use in an operational mode.

The comparative analyses involved the eight soil moisture profile models outlined in table 3. The first analysis compared qualitatively the physical and physiological processes included in each model's program, the way tne processes were presented and implemented by algorithms and program coding, the manner in which soil and crop types were implemented, the number and thickness of soil layers, and the type and character of the input/output data (table 4). The major highlights and limiting factors of these models are summarized in table 5.

The next step toward obtaining the above objectives has been quantitative analyses. One approach has been to perform sensitivity studies, i.e., to vary some of the parameters and variables over representative ranges of values and to analyze the output variation. Another approach has been to compare the output of the models to the output of a modified Van Bavel model (WATBAL2, unpublished). This latter approach was adopted since adequate data sets for testing the models have not been available. A Van Bavel-type model was used because of its dynamic and comprehensive treatment of the soil-plant-atmosphere processes. In addition, if the IBM Continuous System Modeling Program (CSMP III) is available, the program is easy to modify and use.

The Van Bavel model used was a modification of WATBAL1, the model compared in the qualitative analyses. This model was developed under contract for NASA/JSC; and, in order that its characteristics might be determined, it was the first

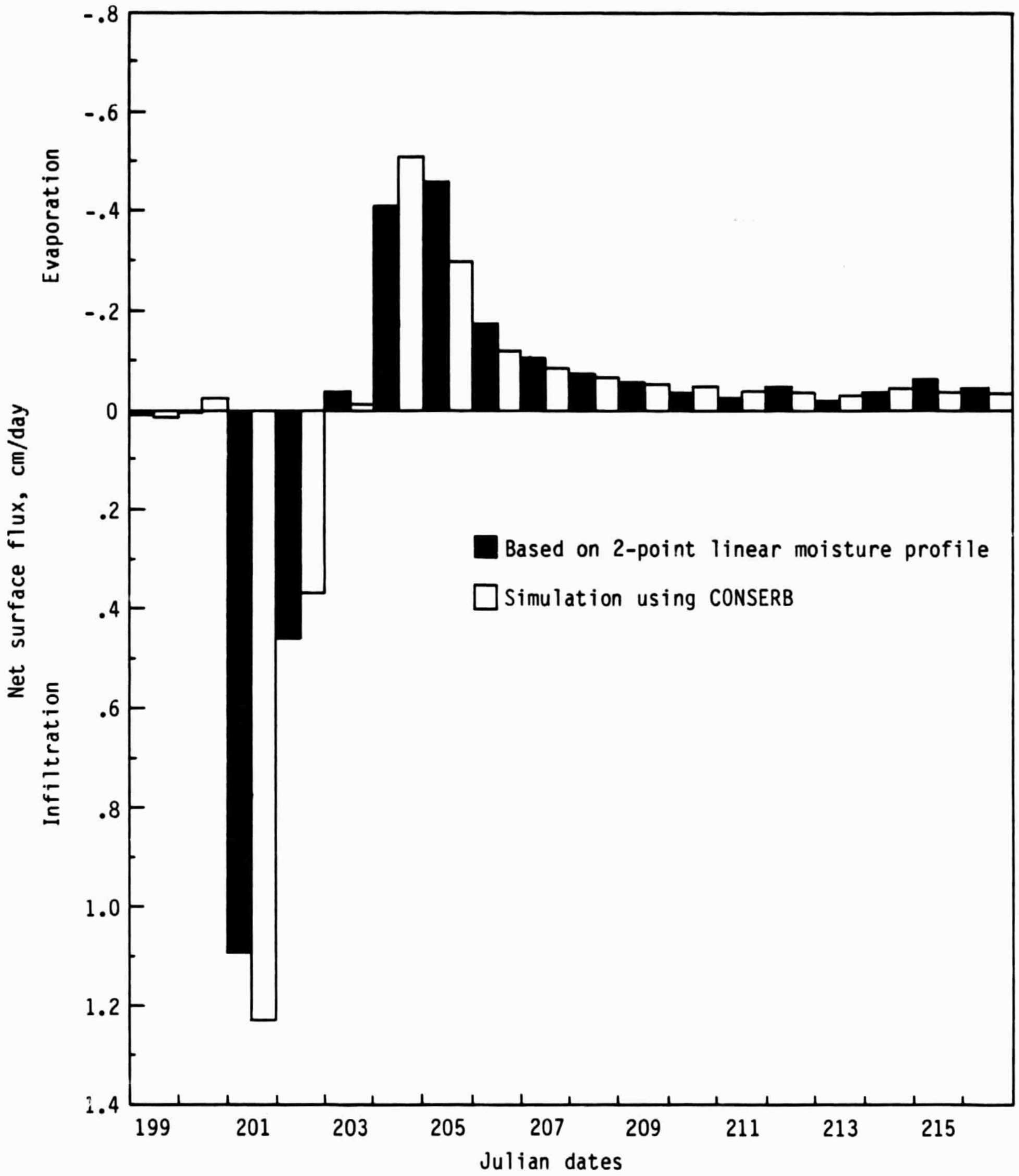

Figure 33.- A comparison of surface fluxes based on two-point linear moisture profiles and the soil moisture model CONSERB.

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TABLE 3.- SUMMARY OF SOIL WATER PROFILE MODELS

Type	Name	Characteristics	Pet function	Crops	Soil	Input	Output
Budget	CMI (Hill version) two layers	ΔSW=P-ET Top layer evaporates first at potential rate	Thornthwaites empirical function; average temperature, day length	Average vegetation	Variable F.C. and W.P. used	See table 2; small input required	See table 2; also compares θm to θn, determines difference, calculates mean difference and RMS; plot θ_p vs. depth
Budget	Baier and Robertson six layers	ΔSW=P-ET-RO-Q See table 3 for details and notation; converts layers to zones with standard percent of total water	Empirical	Spring wheat, soybeans, fallow	Total available water, eight draw-down tables, F.C., W.P.	See table 2; initial SW and SW on other days	See table 2; in addition to daily output, comparative data presented on SW observation day
Budget	Feyerherm six layers	Similar to Baier and Robertson	Similar to Baier Robertson	Winter and spring wheat	Specific table and total water	See table 2; similar to Baier and Robertson	See table 2; not as extensive as Baier and Robertson
Budget	Kanemasu five layers	Similar to Baier and Robertson but more flexible	Energy balance, empirical coefficients, and LAI	Wheat, corn, soybeans, sorghum	Similar to Baier and Robertson	See table 2; more extensive soil and and plant data needed than Baier and Robertson	See table 2; separate E and T value
Budget	SIMBAL (Stuff) 10 layers (needs updating)	ΔSW=P-ET±Q+tile drainage; +Q=C capillary rise from water table	Pan evaporation	Corn	Specific, needs special data for each soil	See table 2; needs depths to tile and water table	See table 2; daily information
Semi-Dynamic	Saxton Variable	ΔSW=P-ET-RO+Q-IC Soil moisture redistribution accomplished by simplified dynamic flow equation	Pan evaporation, empirical relationships	Specified by tables or functions	Similar to Van Bavel and Hanks	See table 2; extensive plant and canopy data, much of which is not readily available; program contains moisture release (θ vs ψ) + hydraulic conductivity data for range of soils	See table 2; compact daily output
Dynamic	Hanks Variable	ΔSW=P-ET-RO±Q Dynamic water flow and variable time step, limited plant capability	Arbitrary, PET or AET	Depends on root and soil data	Depends on ψ(θ) and K(θ) used	See table 2; input periods flexible	See table 2; output time at end of each input period; plot θ vs. depth
Dynamic	Van Bavel Variable	ΔSW=P-ET±Q Dynamic water flow equation, dynamic plant-soil-atmosphere interaction; very flexible, uses CSMPIII, shading output, θ vs. time and depth also available	Evaporation only, energy balance and LAI; uses empirical coefficients	Given by canopy, root and soil data	Given by ψ(θ), K(θ) (soil data) for one or more groups of layers	See table 2; detailed plant soil and atmospheric data needed	See table 2; flexible time increments for all output; calculates crop water use as a function of crop change and S.W. change

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TABLE 4.- INPUT/OUTPUT VERSUS DIFFERENT MODELS

			Palmer (Hill)	VSMB (Baier & Robertson)	VSMB (Feyerherm)	Kanemasu	SIMBAL (Stuff et al.)	Saxton	Hanks	Van Bavel
		Number of layers	2	6	6	5	10	Var.	Var.	Var.
INPUTS	ATMOSPHERE DATA	Precipitation	X	X	X	X	X	X	X	X
		R/RS/RN		X*		X				X
		R outside atmosphere		X	X					
		Mean temperature	X							
		Maximum temperature		X	X	X				X
		Minimum temperature		X	X	X				X
		e_s - e		X*						
		Maximum dewpoint								X
		Minimum dewpoint								X
		Wind run		X*						X
		Pan evaporation					X	X		
		PET (from other source)							X	
		Monthly avg. temps. or avg. max. T. and min. T.			X					
		Monthly avg. pan evap.						X		
		Freezing dates						X		
	PHYSICAL DATA	Latitude		X	X					
		Day length	X							X
		Snow melt coeff.		X	X					
		Snow melt tables		X	X					

*Used only if data are available.

TABLE 4.- Continued.

		Palmer (Hill)	VSMB (Baier & Robertson)	VSMB (Feyerherm)	Kanemasu	SIMBAL (Stuff et al.)	Saxton	Hanks	Van Bavel
	Number of layers	2	6	6	5	10	Var.	Var.	Var.
INPUTS / SOIL DATA	Actual θ vs. layer or depth						X	X	X
	Available (θ-WP) vs. layer/depth	X	X	X	X				
	Percent available θ vs. layer/depth					X			
	Extractable θ vs. layer/depth								
	Maximum available θ/MXH2O		X	X	X				
	θ maximum (F.C)	X	X	X	X	X	X		
	θ minimum (W.P)	X	X	X	X	X	X		
	θ saturated						X	X	
	Minimum extractable θ							X	
	Hydraulic conductivity [K(θ)]						X	X	X
	Moisture release data [ψ(θ)]						X	X	X
	Water table depth					X			
	Tile depth					X			
	T_V				X				
	TIN				X				
	T_5				X				
	U				X				
	α				X				
	FALLRT				X				
	Soil const.				X				
	X5				X				
	Salt profile vs. depth							X	
	Salt parameters							X	

TABLE 4.- Continued.

		Palmer (Hill)	VSMB (Baier & Robertson)	VSMB (Feyerherm)	Kanemasu	SIMBAL (Stuff et al.)	Saxton	Hanks	Van Bavel
	Number of layers	2	6	6	5	10	Var.	Var.	Var.
INPUTS — SOILS DATA	Soil albedo								
	TAU values				X				
	Runoff (daily)						X		
	Avg. runoff coefficients						X		
	Irrigation (called out)				X			X	
	Infiltration/runoff coefs.		X	X	X				
	Soil characteristic tables (draw-down)		X	X					
	Lysimeter data (or PET data)							X	

TABLE 4.- Continued.

			Palmer (Hill)	VSMB (Baier & Robertson)	VSMB (Feyerherm)	Kanemasu	SIMBAL (Stuff et al.)	Saxton	Hanks	Van Bavel
		Number of layers	2	6	6	5	10	Var.	Var.	Var.
INPUTS	PLANT DATA	Crop type		X	X	X				
		Crop stage and dates		X		X				
		Planting date			X	X	X			
		Other crop dates						X		
		Leaf area index (LAI)				X				X
		Root distribution by stages		X	X	X				
		Other root distribution data						X	X	X
		Growing degree days (GDD)				X				
		Bio-meteorological coeffs.			X	X				
		Minimum and maximum root potentials							X	
		Root resistance							X	
		Specific resistance of plant to water uptake								X
		Crop water potential at zero transpiration								X
		Crop stomatal resistance vs. crop water potential table								X
		Phenology susceptibility data						X		
		Other phenology data						X		
		Canopy cover susceptibility data						X		
		Other canopy cover data						X		
		Moisture stress curve data						X		
		Rain interception data						X		

TABLE 4.- Continued.

		Palmer (Hill)	VSMB (Baier & Robertson)	VSMB (Feyerherm)	Kanemasu	SIMBAL (Stuff et al.)	Saxton	Hanks	Van Bavel
	Number of layers	2	6	6	5	10	Var.	Var.	Var.
INPUTS – PLANT DATA	Yield susceptibility data						X		
	Silking date					X			
	Sowing depth and rate								
	Genetic specific coeffs.			X					
	Time to mature root profile							X	
	Days to start of cover growth							X	
	Days to maximum effective cover growth							X	
	Depth of root system								X
	Other plant growth or yield parameters			X	X				
	Management and productivity factor			X					

TABLE 4.- Continued.

		Palmer (Hill)	VSMB (Baier & Robertson)	VSMB (Feyerherm)	Kanemasu	SIMBAL (Stuff et al.)	Saxton	Hanks	Van Bavel
	Number of layers	2	6	6	5	10	Var.	Var.	Var.
DERIVED DATA — OUTPUT	PET	X	X	X(1)	X		X		
	AET	X	X	X(1)	X	X	X		X
	Evaporation (soil)				X		X	X	X
	Leaf interception evaporation						X		
	Transpiration				X		X	X	X
	ET due to excess temperatures				X				
	Actual θ by layer or depth					X	X	X	X
	Available θp by layer or depth	X	X	X(1)	X				
	Total water in profile		X	X(1)	X	X	X		X
	Recharge	X							
	Runoff	X	X	X(1)	X			X	
	Infiltration		X	X(1)		X	X		X
	Snow melt amount		X	X(1)					
	Capillary rise					X			
	Drainage (out bottom of profile)		X	X(1)	X	X	X	X	X
	Tile drainage					X			
	Water table change					X			
	Percent available water (PAV) in root zone					X			
	θ flux at layer boundary								X
	Net flux by layer								X
	Surface flux							X	X
	Cumulative surface flow							X	
	Net change H_2O in column							X	
	(Cum. water flow)								

(1)Available but not printed in output.

TABLE 4.- Concluded.

		Palmer (Hill)	VSMB (Baier & Robertson)	VSMB (Feyerherm)	Kanemasu	SIMBAL (Stuff et al.)	Saxton	Hanks	Van Bavel
	Number of layers	2	6	6	5	10	Var.	Var.	Var.
DERIVED DATA	OUTPUT								
	Layer depletion				X				
	Plot θ observed	X							
	Plot θp vs. depth	X						X	
	Shading plot θp vs. depth and time								X
	Salt profile plot							X	
	Diffusivity by layer							X	
	Pressure potential vs. depth							X	X
	Root distribution							X	X
	Root uptake of water by layer								X
	Crop cover				X				
	BMTS/phenology information			X	X		X		
	Canopy temperature								X
	Difference between observed and predicted θ	X	X						
	Statistical estimates	X							
	Stress factor					X	X	X	
	Crop and yield information			X			X	X	
	Root water potential							X	
	Other soil water, ET and salt parameters							X	

TABLE 5.- COMPARATIVE SUMMARY OF PERFORMANCE ABILITY OF SOIL MOISTURE MODELS

Highlights	Limiting factors
Palmer	
• Uses readily available meteorological data • Requires minimum input data • Long usage	• Determines average weekly changes for general cropland • Two-layer model • Runoff only when profile filled • Limited number of processes modeled
VSMB	
• Uses readily available meteorological data with options to use more if available • Takes into account freezing soil and snow • Used extensively in Canada	• Developed for Canadian soils, crops, and climate
Feyerherm	
• Uses readily available meteorlogical data	• No profile printout • Crop and soil specific
Kanemasu	
• Tested for several crops • Five layers	• Soil and crop specific • Uses solar radiation only • Many empirical constants
SIMBAL	
• For poorly drained soil • Small amount of input data needed	• Crop and soil specific; highly empirical; many coefficients • Uses pan evaporation
Saxton's SPAW	
• Includes data for wide range of soils • Calculates stress • Has feedback • Represents many processes	• Needs crop data not readily available • Uses pan evaporation

TABLE 5.- Concluded.

Highlights	Limiting factors
Hanks	
• Dynamic model • Extensively tested and used • Prints depth profile	• Needs hydrologic data for specific soil • Needs ET estimates • Needs canopy and root depth
Van Bavel	
• Dynamic and flexible • Ease of programming and use • Calculates E and T directly from meteorological data • Several new approaches	• Not tested • Complex • Uses CSMPIII which may not be readily available

profile model subjected to a sensitivity analysis. The results of that analysis have been published (Hildreth, Mar. 1981). In general, the model produced for fallow fields the typical characteristics of evaporation and moisture profile change. However, the algorithm for determining water uptake from the soil by transpiration had an undesirable characteristic in the drier soil moisture regimes and was replaced by a simpler algorithm. This modified program, WATBAL2, then produced the typical evaporation, transpiration, drainage, and profile water changes. Examples of the responses are shown in figures 34 and 35.

WATBAL1 and WATBAL2 were also used to compare several models that determine the soil moisture characteristic data. This comparison involved models by Ghosh (1976), by Rogowski (1971), and by Arya and Paris (1981).

A sensitivity study of Saxton's SPAW model was also completed during this period. In general, the transpiration part of the model compared well with WATBAL2; however, the evaporation module did not reproduce typical characteristics with realistic parameter values and may need modification.

The comparison of SPAW to WATBAL2 was performed using soil moisture characteristic data representing Keith silt loam, as determined by the Rogowski model (1971), and hydraulic conductivities determined in turn from these values by Jackson's method (1972). The two profile models were then run, using Colby weather conditions for 100 days, for both fallow and crop conditions. The fallow simulations provided profiles that could be made quite close in values when the parameters in the evaporation algorithms of SPAW were suitably selected. The profile simulations for crops, however, were more difficult to make exactly the same because crop parameters work differently in the two models. The analyses of these simulations are nearly complete.

In addition to the above, Van Bavel and Lascano's CONSERB program (1979) was implemented and used in several ways. CONSERB simulates both moisture and temperature profiles simultaneously in the soil under fallow conditions. However, CONSERB requires about five times more central processing unit (CPU) time than

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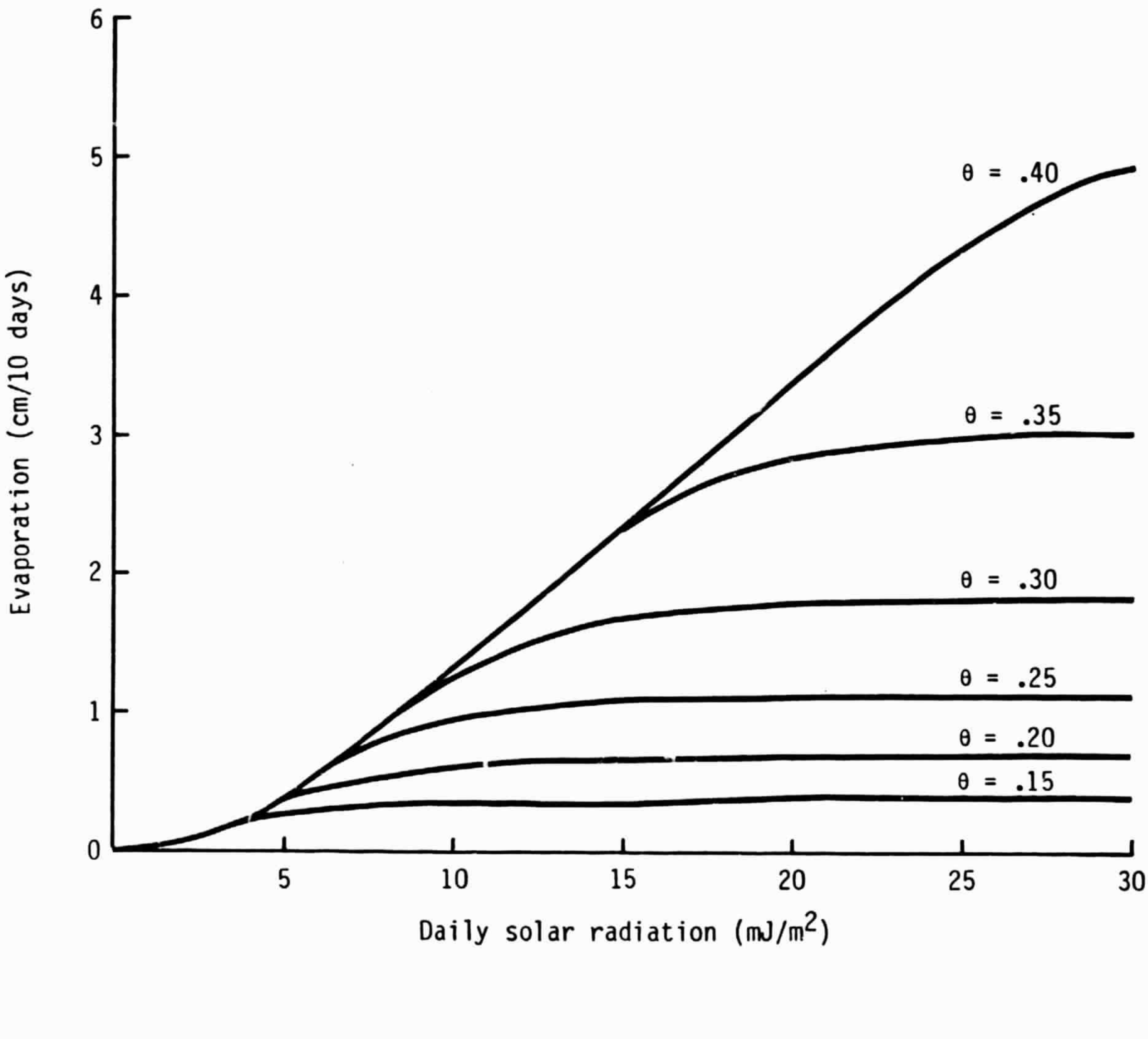

Figure 34.- The changes in the evaporation for 10 days versus the daily solar radiation and initial water profile using the modified Van Bavel model, WATBAL2, for fallow fields.

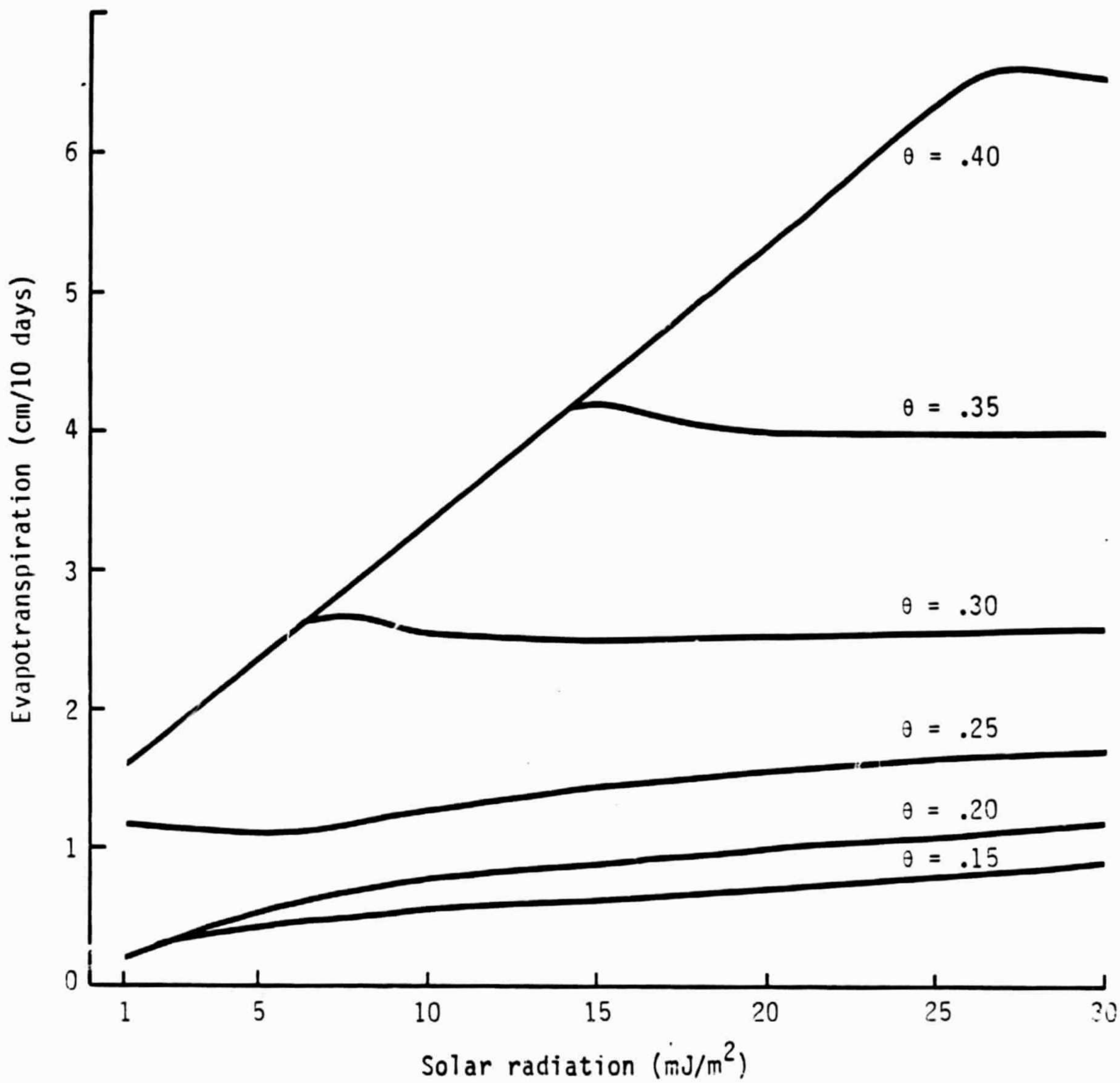

Figure 35.- The changes in evapotranspiration for 10 days versus the daily radiation amount and the initial soil water profile using the modified Van Bavel model, WATBAL2, for crop fields.

the WATBAL2 fallow model. CONSERB was used to simulate detailed moisture and temperature profiles at different times during the day for given fallow fields at Colby.

5.12 USE OF MEASURED SOIL MOISTURE DATA FOR AGRICULTURAL APPLICATIONS

In FY 1981, KSU continued its investigation of the potential uses of remotely sensed soil moisture data for agricultural applications. A major accomplishment was the publication of results of their FY 1980 workshop on the uses of such information for crop yield prediction. In this report (Kanemasu and Lawlor, 1980), results were given for sensitivity analyses of two winter wheat yield prediction models, Kanemasu's evapotranspiration (ET) model and Ritchie's wheat model (unpublished).

The sensitivity analyses were based on climatic data for 10 years (1969 through 1979) for Manhattan, Kansas. Soil-moisture-related parameters were varied, one at a time, and the yield-estimate departures from the baseline mean were calculated and tabulated for the 10-year period. The soil-moisture-related parameters investigated included soil moisture (in the root zone) at the time of planting, maximum available water content (in the root zone), rainfall, and planting date (which might be affected by wet conditions in the field at a desired time of planting). The results of the sensitivity analyses are shown in tables 6 through 13. The boxed values in these tables represent the baseline conditions and yields.

The values of sensitivity derived from the analysis of Kanemasu's model are probably invalid, since the leaf area index (LAI) did not vary in the model (even though water parameters did). In a moisture-stress-limiting situation, LAI would be expected to change as water contents are changed.

From the data presented in tables 6 through 13, the authors computed the errors in initial water content, maximum available water content, rainfall, and planting date that would yield a 5-percent change in the modeled yield for the mean conditions of the input data and at the dry extreme of the data. The results of

TABLE 6.- SIMULATED MEAN GRAIN YIELDS AND STANDARD DEVIATIONS FROM RITCHIE'S MODEL OVER A 10-YEAR PERIOD, VARYING ONLY THE INITIAL SOIL MOISTURE

Initial soil moisture, in.	Yield, bu/acre	Standard deviation, bu/acre
11.74	70.7	31.6
$\boxed{9.74}$	$\boxed{70.7}$	$\boxed{31.6}$
7.74	70.2	32.0
5.74	68.2	33.9
3.74	61.8	36.9

TABLE 7.- SIMULATED MEAN GRAIN YIELDS AND STANDARD DEVIATIONS FROM RITCHIE'S MODEL OVER A 10-YEAR PERIOD, VARYING ONLY THE MAXIMUM AVAILABLE WATER

Maximum available water, in.	Yield, bu/acre	Standard deviation, bu/acre
15.7	79.2	30.0
13.7	78.2	30.0
11.7	76.2	30.5
$\boxed{9.7}$	$\boxed{70.7}$	$\boxed{31.6}$
7.7	60.2	34.8
5.7	44.3	33.0
3.7	35.9	29.9

TABLE 8.- SIMULATED MEAN GRAIN YIELDS AND STANDARD DEVIATIONS FROM RITCHIE'S MODEL OVER A 10-YEAR PERIOD, VARYING ONLY THE RAINFALL

Rainfall decrease (from actual), in.	Yield, bu/acre	Standard deviation, bu/acre
$\boxed{0.00}$	$\boxed{70.7}$	$\boxed{31.6}$
.10	67.4	31.6
.20	63.8	32.1
.40	51.2	30.8
.60	33.7	23.2

TABLE 9.- SIMULATED MEAN GRAIN YIELDS AND STANDARD DEVIATIONS FROM RITCHIE'S MODEL OVER A 10-YEAR PERIOD, VARYING ONLY THE PLANTING DATE

Planting date	Yield, bu/acre	Standard deviation, bu/acre
8-29	67.2	30.3
9-3	67.6	29.8
9-13	68.3	32.9
9-18	67.5	32.1
9-23	71.4	32.1
$\boxed{9\text{-}28}$	$\boxed{70.7}$	$\boxed{31.6}$
10-3	64.9	34.6
10-8	62.7	33.6
10-13	55.9	33.4
10-18	52.5	34.1
10-23	48.4	33.1
10-28	44.1	33.0

TABLE 10.- SIMULATED MEAN YIELDS AND STANDARD DEVIATIONS FROM KANEMASU'S MODEL OVER A 10-YEAR PERIOD, VARYING ONLY THE INITIAL WATER CONTENT

Initial water content, in.	Yield, bu/acre	Standard deviation, bu/acre
17	60.4	8.7
$\boxed{15}$	$\boxed{60.4}$	$\boxed{8.8}$
13	59.7	8.9
9	53.6	12.8

TABLE 11.- SIMULATED MEAN YIELDS AND STANDARD DEVIATIONS FROM KANEMASU'S MODEL OVER A 10-YEAR PERIOD, VARYING ONLY THE MAXIMUM AVAILABLE WATER

Maximum available water, in.	Yield, bu/acre	Standard deviation, bu/acre
$\boxed{15}$	$\boxed{60.4}$	$\boxed{8.8}$
13	60.4	8.7
9	58.7	9.6
5	47.8	14.9

TABLE 12.- SIMULATED MEAN YIELDS AND STANDARD DEVIATIONS FROM KANEMASU'S MODEL OVER A 10-YEAR PERIOD, VARYING ONLY THE PRECIPITATION AMOUNTS

Rainfall decrease (from actual), in.	Yield, bu/acre	Standard deviation, bu/acre
$\boxed{0.00}$	$\boxed{60.4}$	$\boxed{8.8}$
.10	60.2	8.5
.20	59.5	8.7
.40	54.6	10.2
.60	41.3	13.5

TABLE 13.- SIMULATED MEAN YIELDS AND STANDARD DEVIATIONS FROM KANEMASU'S MODEL OVER A 10-YEAR PERIOD, VARYING ONLY THE PLANTING DATE

Planting date	Yield, bu/acre	Standard deviation, bu/acre
8-29	60.9	8.4
$\boxed{9\text{-}8}$	$\boxed{60.4}$	$\boxed{8.8}$
9-18	60.5	8.0
9-28	60.2	8.5
10-8	57.7	10.4
10-18	52.8	8.3
10-28	49.3	8.8

this analysis are shown in table 14. These data show that errors in the estimation of initial water content have the smallest impact on yield estimates. The estimation of maximum available water content (water-holding capacity) is especially important for soils having low values for this parameter. Also, errors in rainfall estimation are important when rainfall amounts are low.

These data, while interesting, are not conclusive and do not address the real issues:

- What is the need for surface-zone soil moisture measurements obtained by remote sensing?
- What are the accuracy (absolute error), frequency (revisit interval), and minimum areal size (spatial resolution) required in such measurements in order to make a significant improvement over competing agricultural prediction systems that deal with such areas as development, yield, and irrigation management?

To address these issues, different models are needed which can accurately predict surface-zone soil moisture and similar important information (such as surface flux) and can directly employ surface-zone soil moisture information useful for agricultural applications. KSU is developing such a model in FY 1982 to address this issue for small grains. LARS is doing the same for corn and soybeans. Lockheed-EMSCO is considering the case for bare soil and fallow.

TABLE 14.- ERRORS ALLOWABLE IN RITCHIE'S MODEL INPUTS THAT PRODUCE A 5-PERCENT ERROR IN THE YIELD FOR MEAN AND DRY CONDITIONS

Input parameter	Allowed error of input	
	For mean conditions	For dry conditions
Initial soil water content	3.3 in.	1.0 in.
Maximum available water content	1.0 in.	0.6 in.
Seasonal rainfall total	11 %	3 %
Planting date	3 days	3 days*

*For late planting.

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